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(54) SEMICONDUCTOR LASER WITH INTEGRAL SPATIAL MODE FILTER

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(73) Assignee: **SDL, Inc.**, San Jose, CA (US)

(21) Appl. No.: **09/418,905**

(22) Filed: **Oct. 15, 1999**

Related U.S. Patent Documents

Reissue of:
(64) Patent No.: **5,602,864**
Issued: **Feb. 11, 1997**
Appl. No.: **08/393,136**
Filed: **Feb. 21, 1995**

U.S. Applications:
(62) Division of application No. 08/263,190, filed on Jun. 21, 1994, now Pat. No. 5,592,503, which is a division of application No. 08/001,735, filed on Jan. 7, 1993, now Pat. No. 5,392,308.

(51) **Int. Cl.**^{7} **H01S 3/19**
(52) **U.S. Cl.** **372/50**; 372/46; 372/96; 372/101; 372/102
(58) **Field of Search** 372/44–46, 49, 372/50, 97, 101, 102, 99, 100, 96, 20, 32, 98

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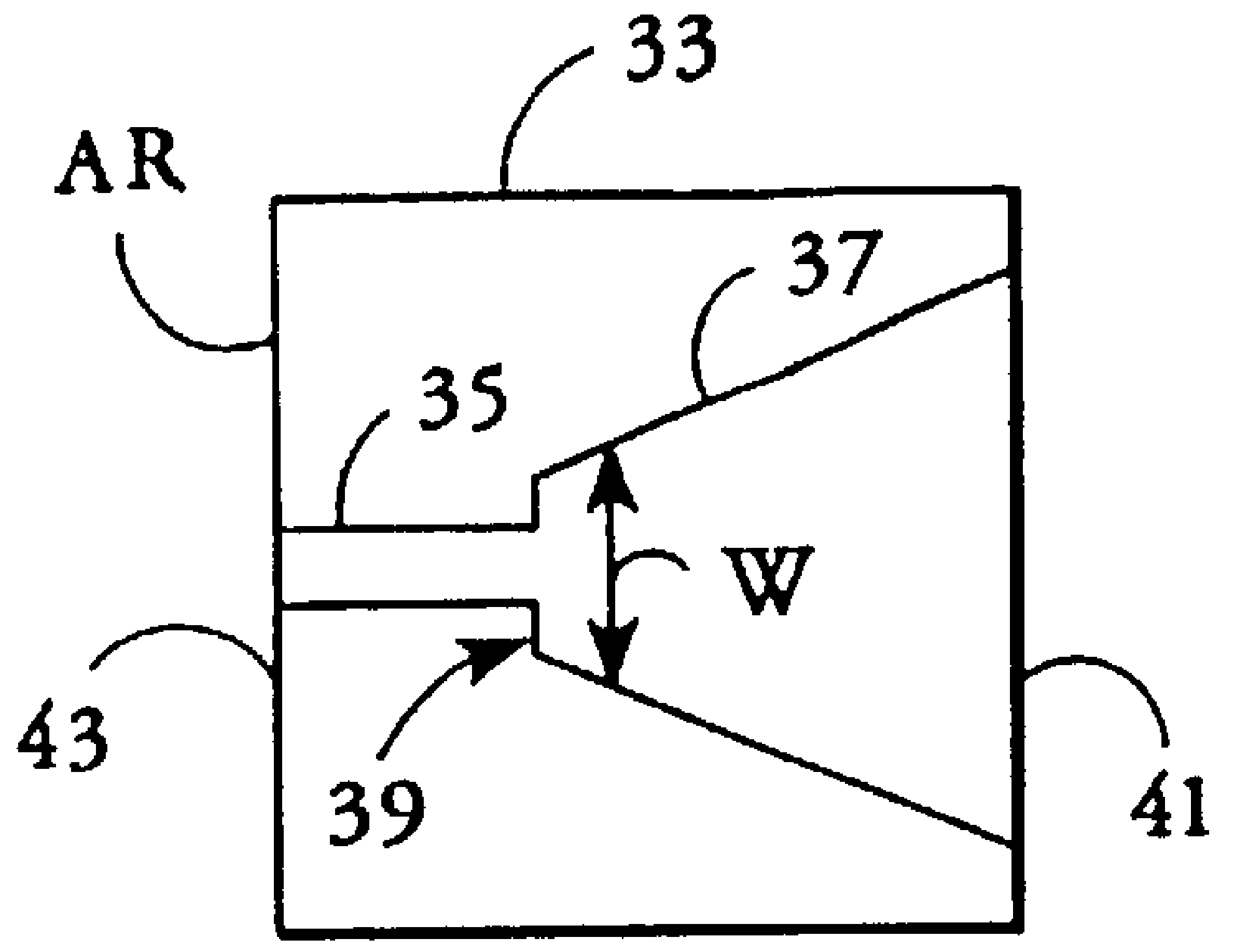
(57) ABSTRACT

A semiconductor laser having a light amplifying diode heterostructure with a flared gain region in an external resonant cavity. The flared gain region has a narrow aperture end which may be coupled to a single mode waveguide and a wide output end. A light emitting surface of the heterostructure proximate to the wide end of the flared gain region is partially reflective and combines with an external reflector to form a resonant cavity that is effectively unstable. The intracavity light-emitting surface proximate to the narrow aperture end is antireflection coated. The external reflector may be a planar mirror or a grating reflector. A lens or an optical fiber may couple the aperture end of the flared gain region to the external reflector. Frequency-selective feedback is provided by orienting the grating reflector or providing a prism in the cavity in front of the external planar mirror. Other filtering elements may also be placed in the external cavity. The flared gain region and waveguide may be differentially pumped or modulated with current provided by separate contacts.

59 Claims, 12 Drawing Sheets



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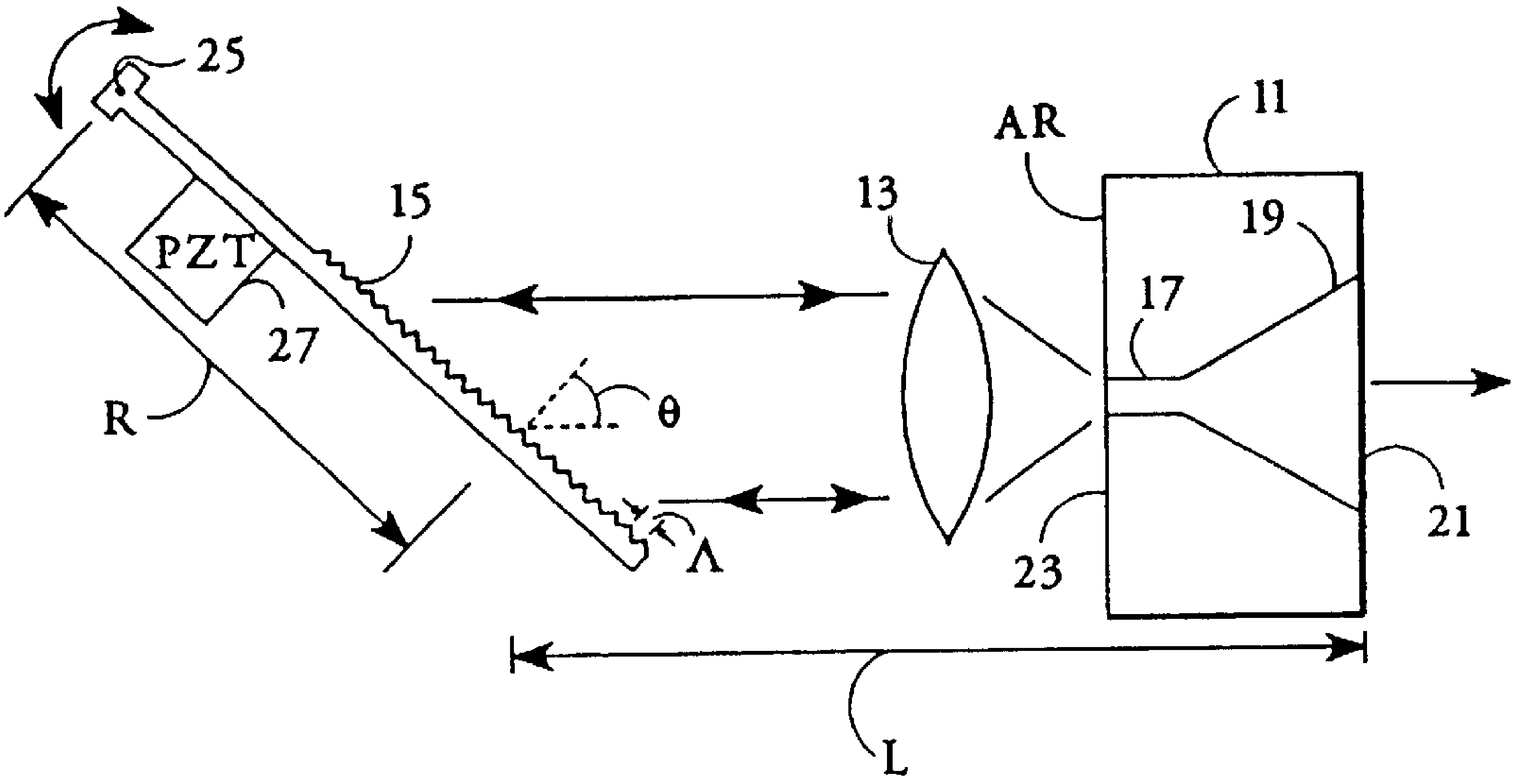


FIG. 1

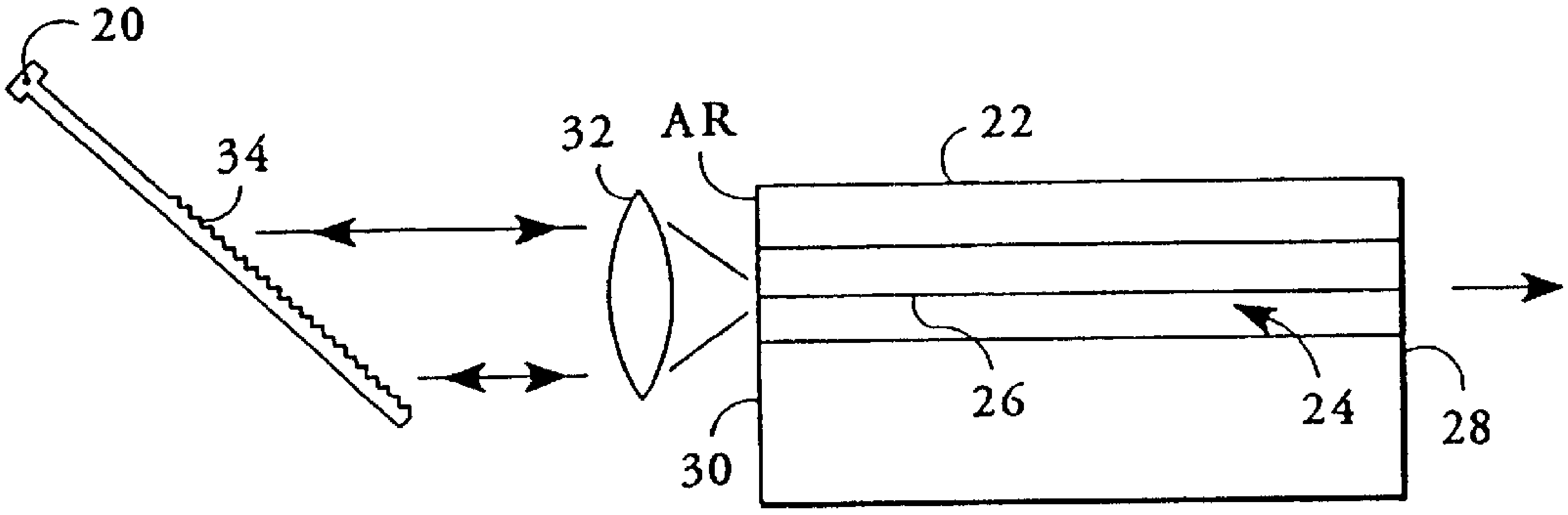


FIG. 2

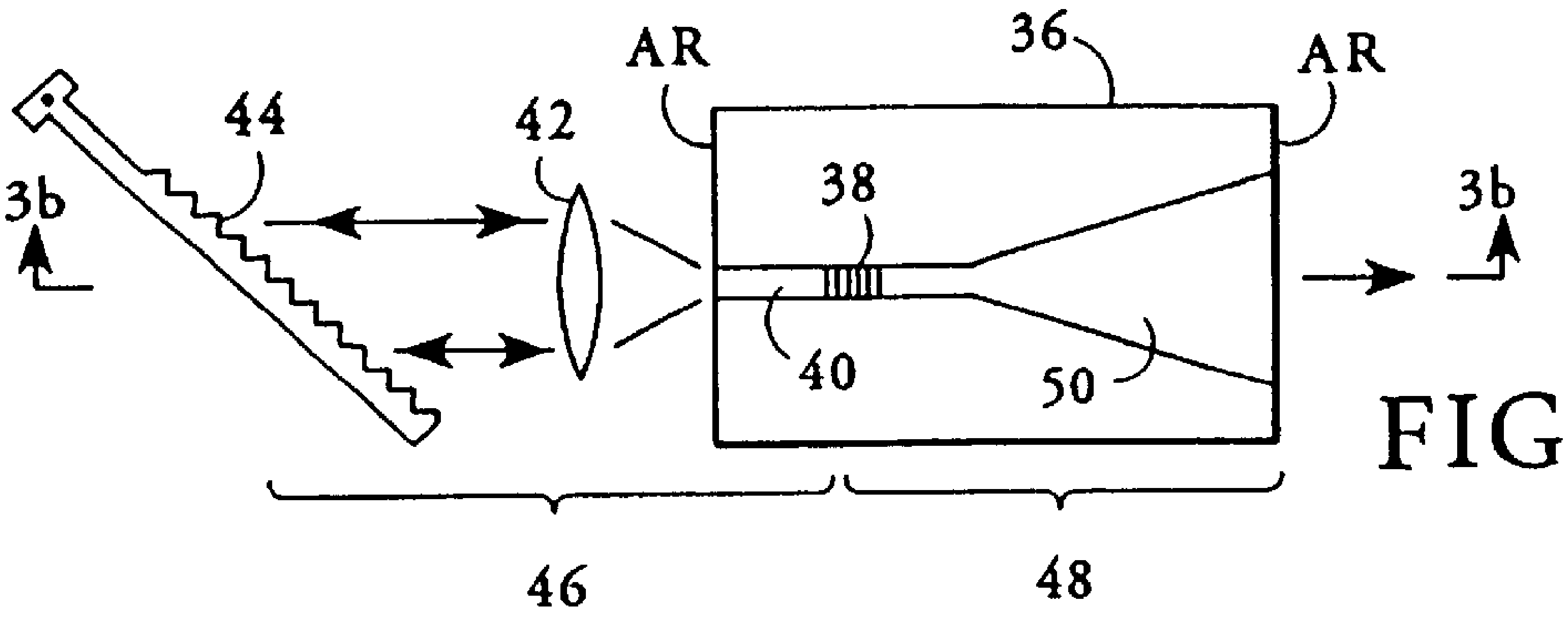


FIG. 3a

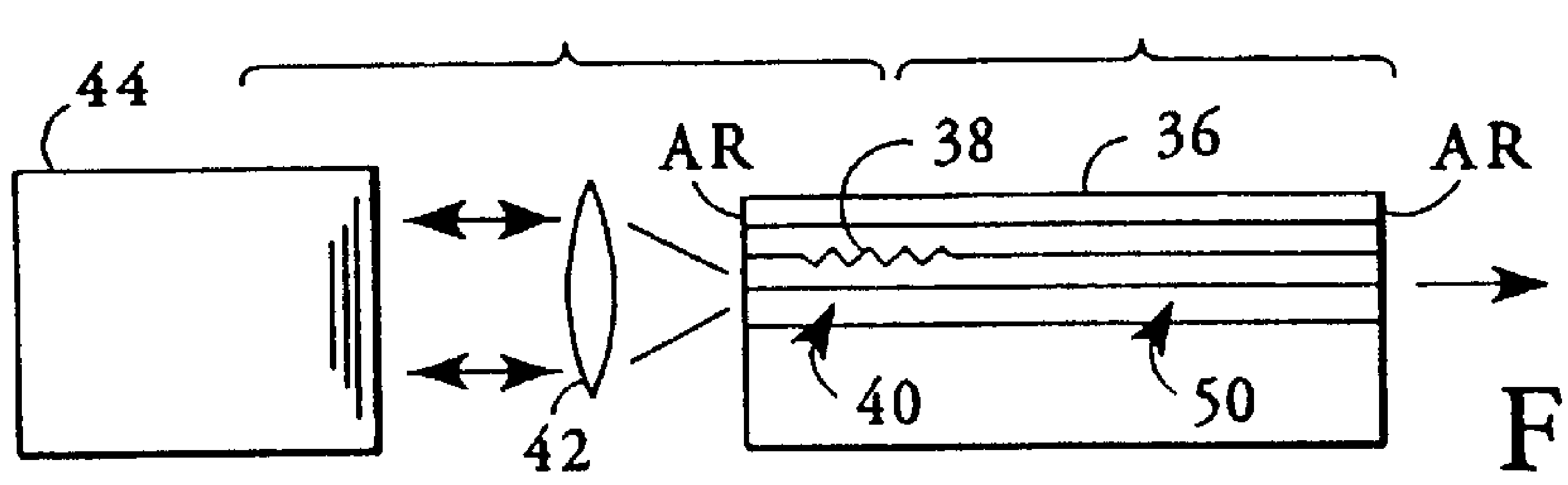
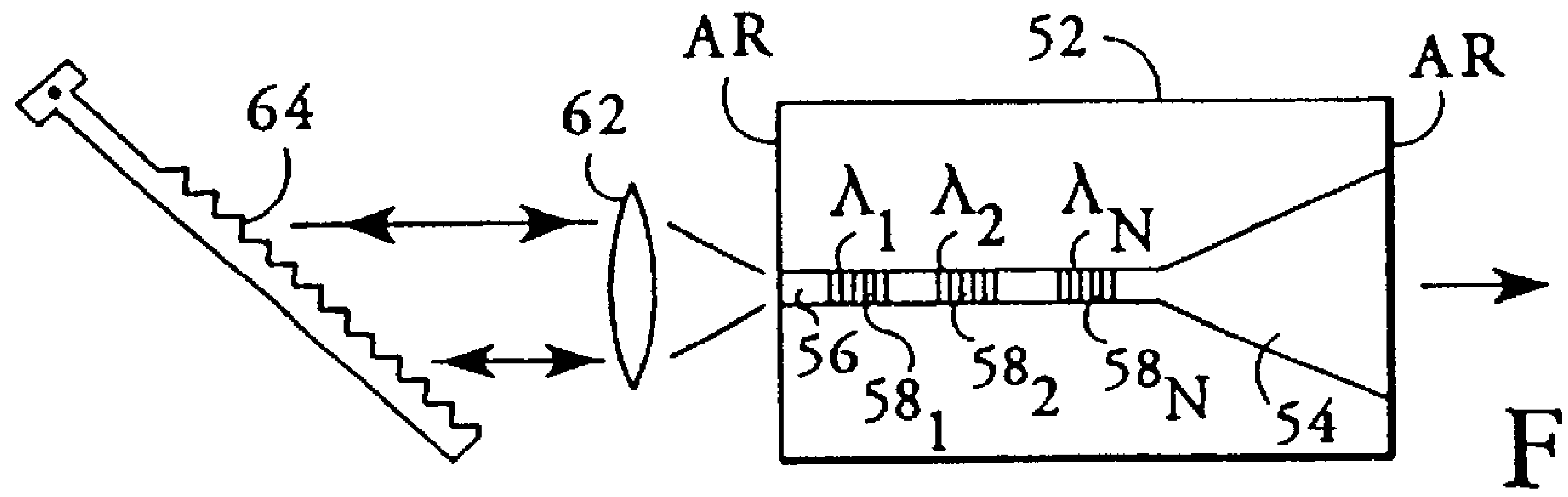


FIG. 3b



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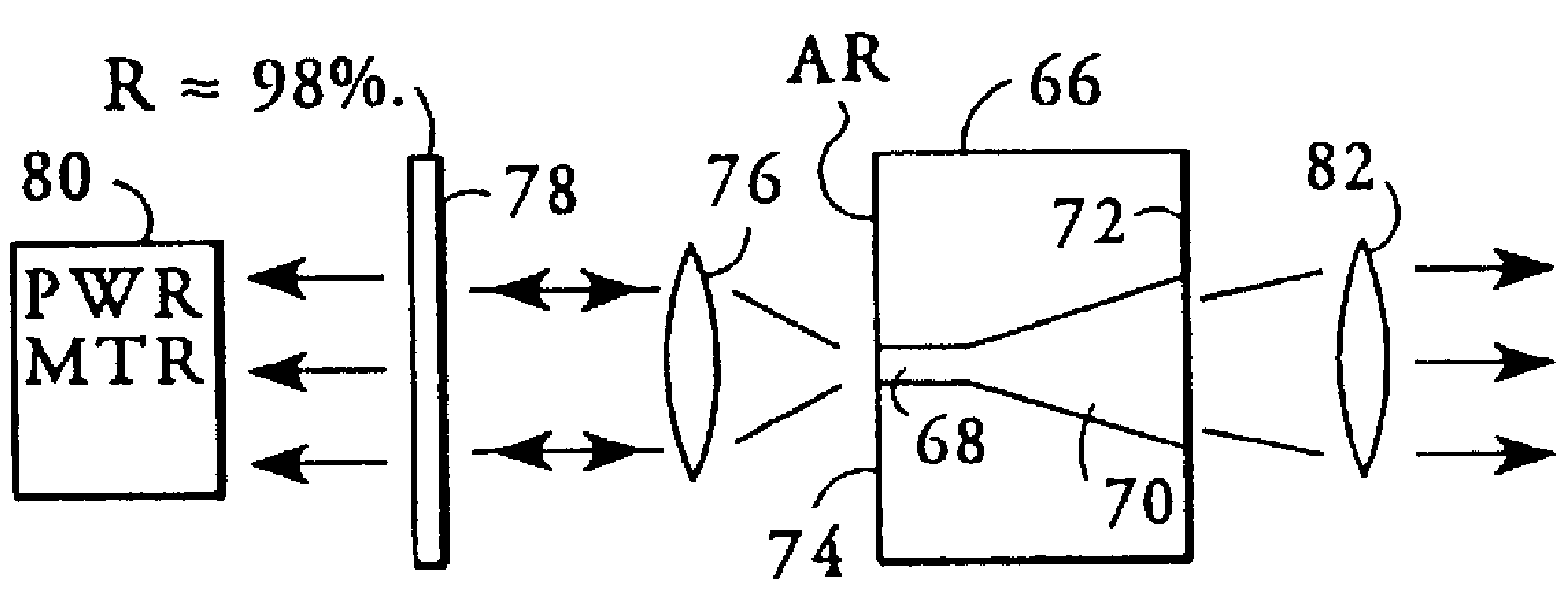

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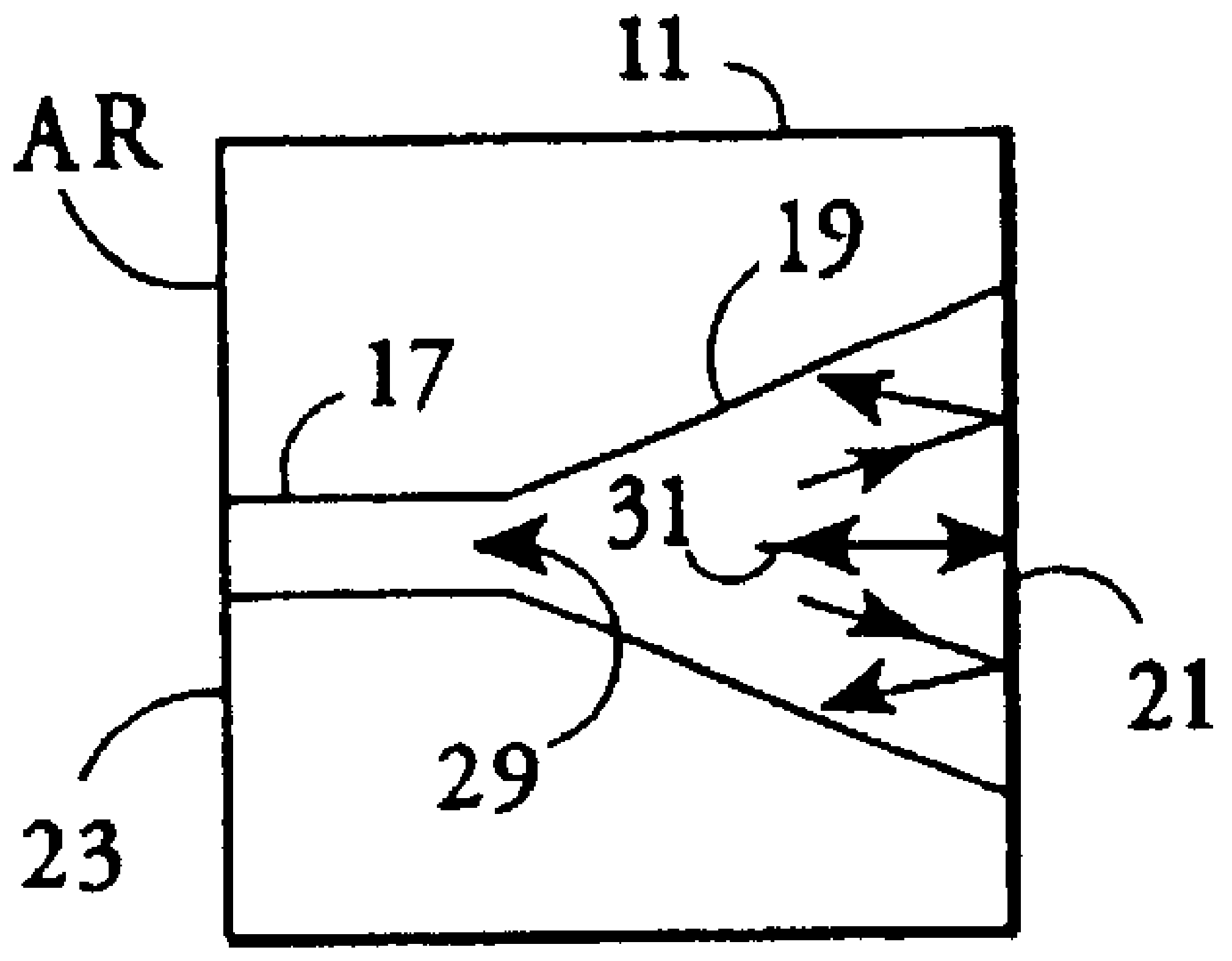
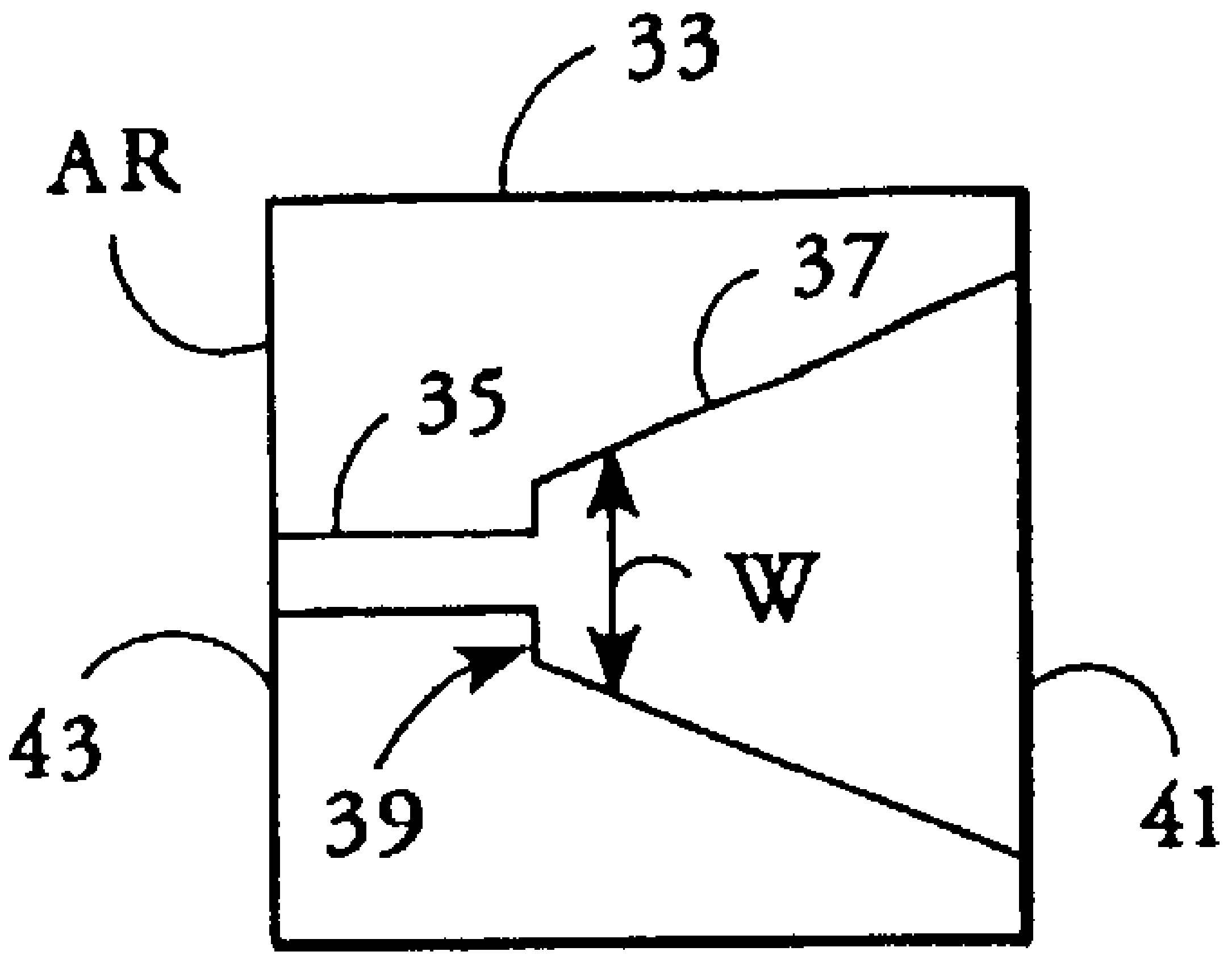


FIG. 6a



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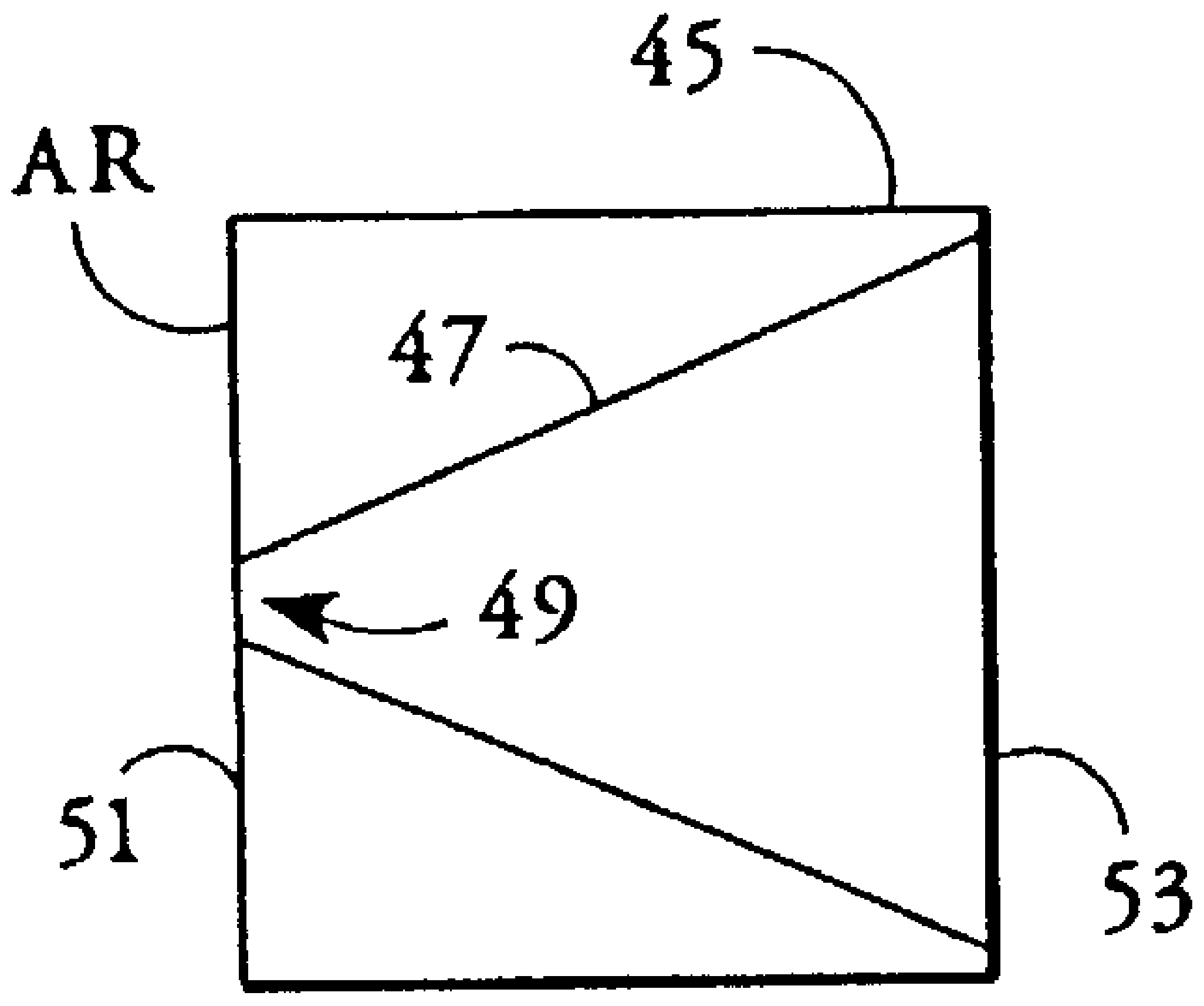


FIG. 6c

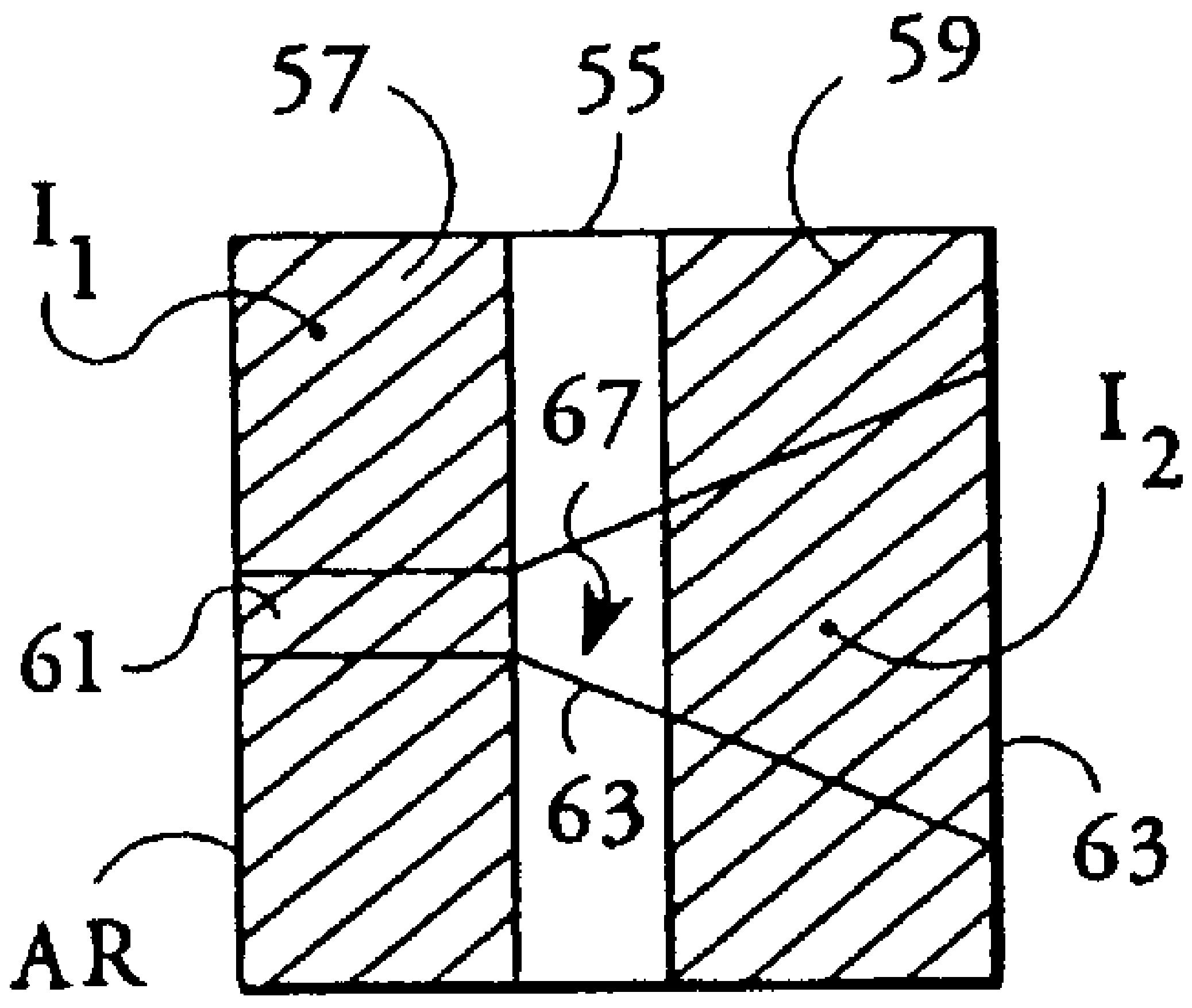
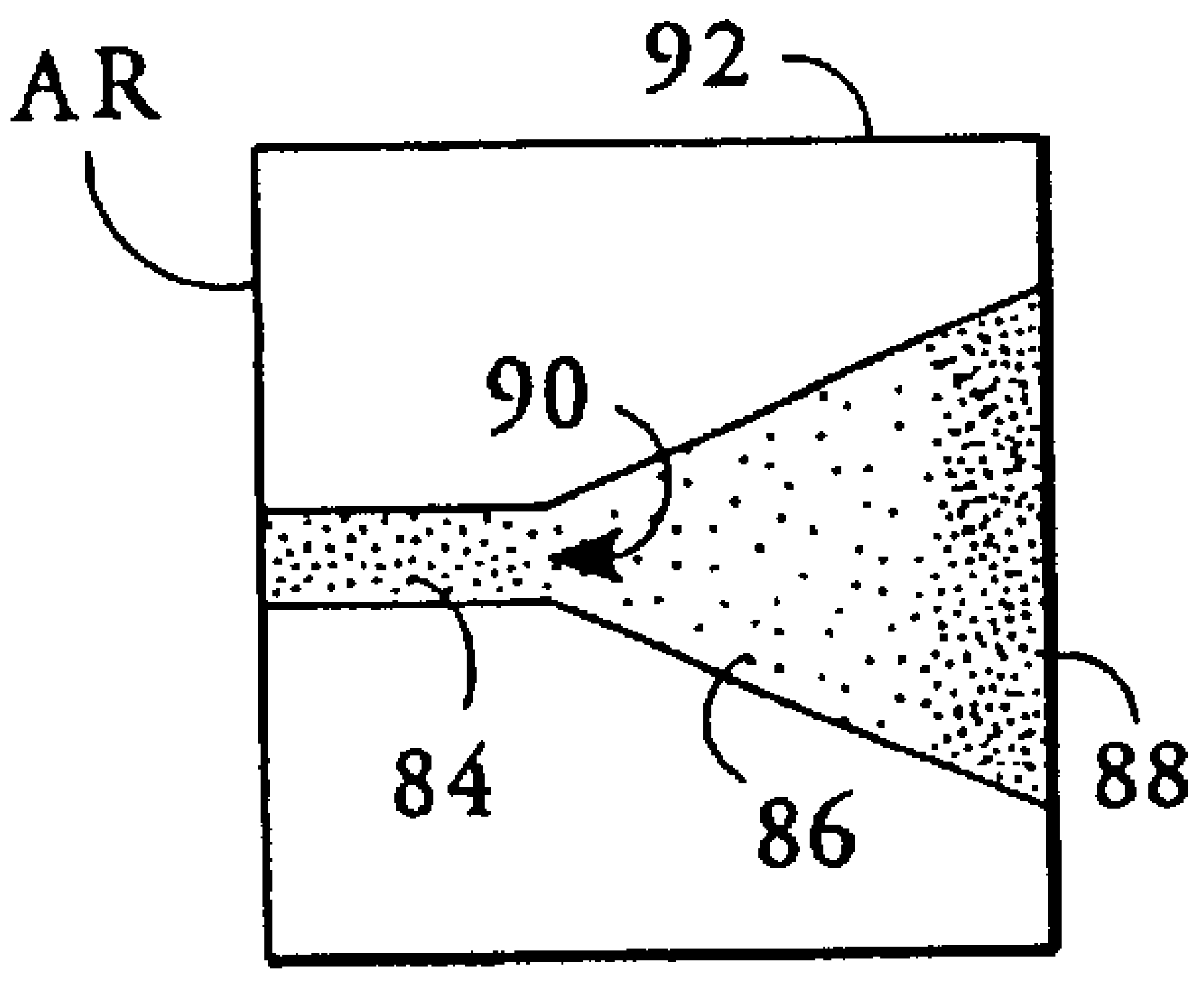


FIG. 6d



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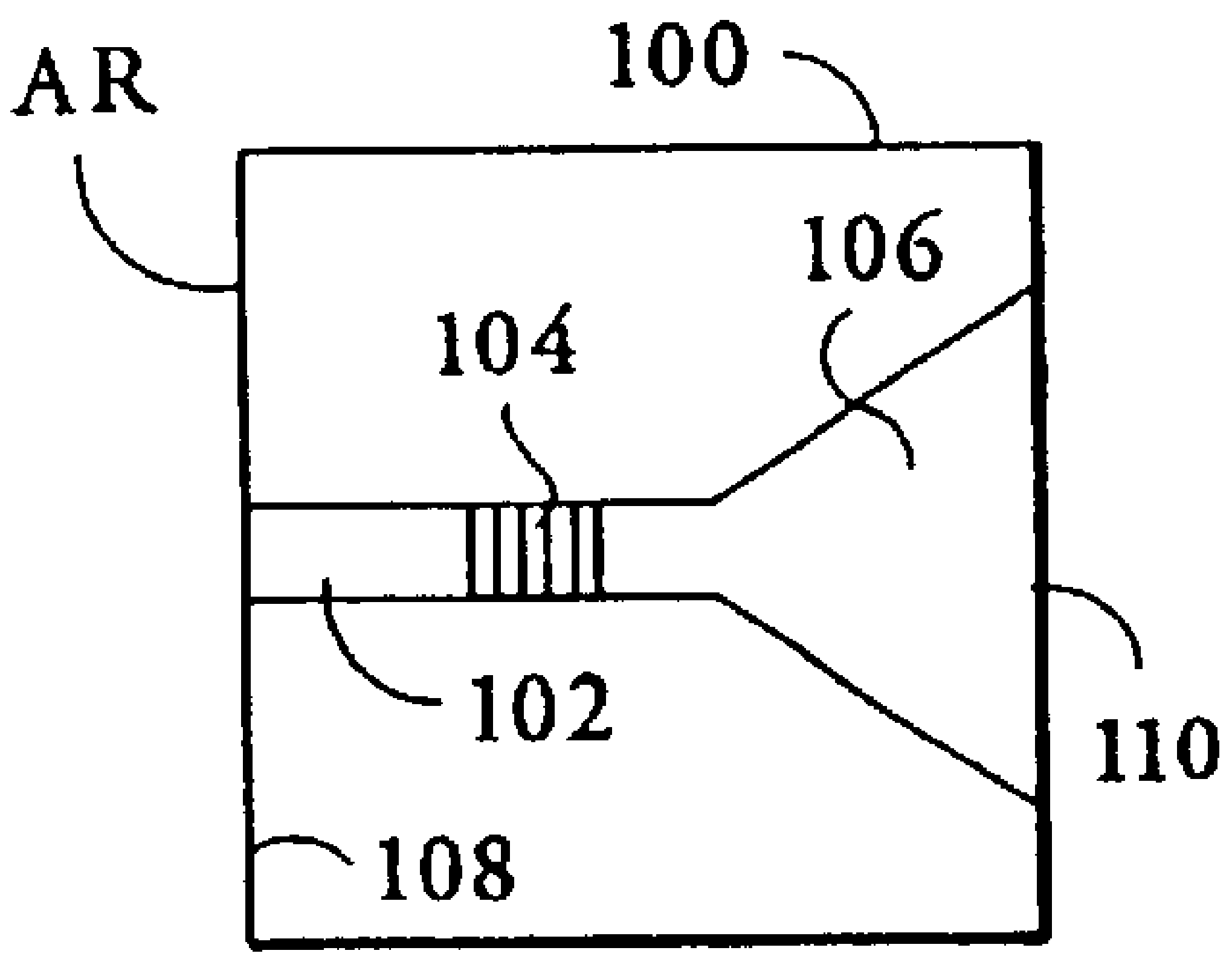

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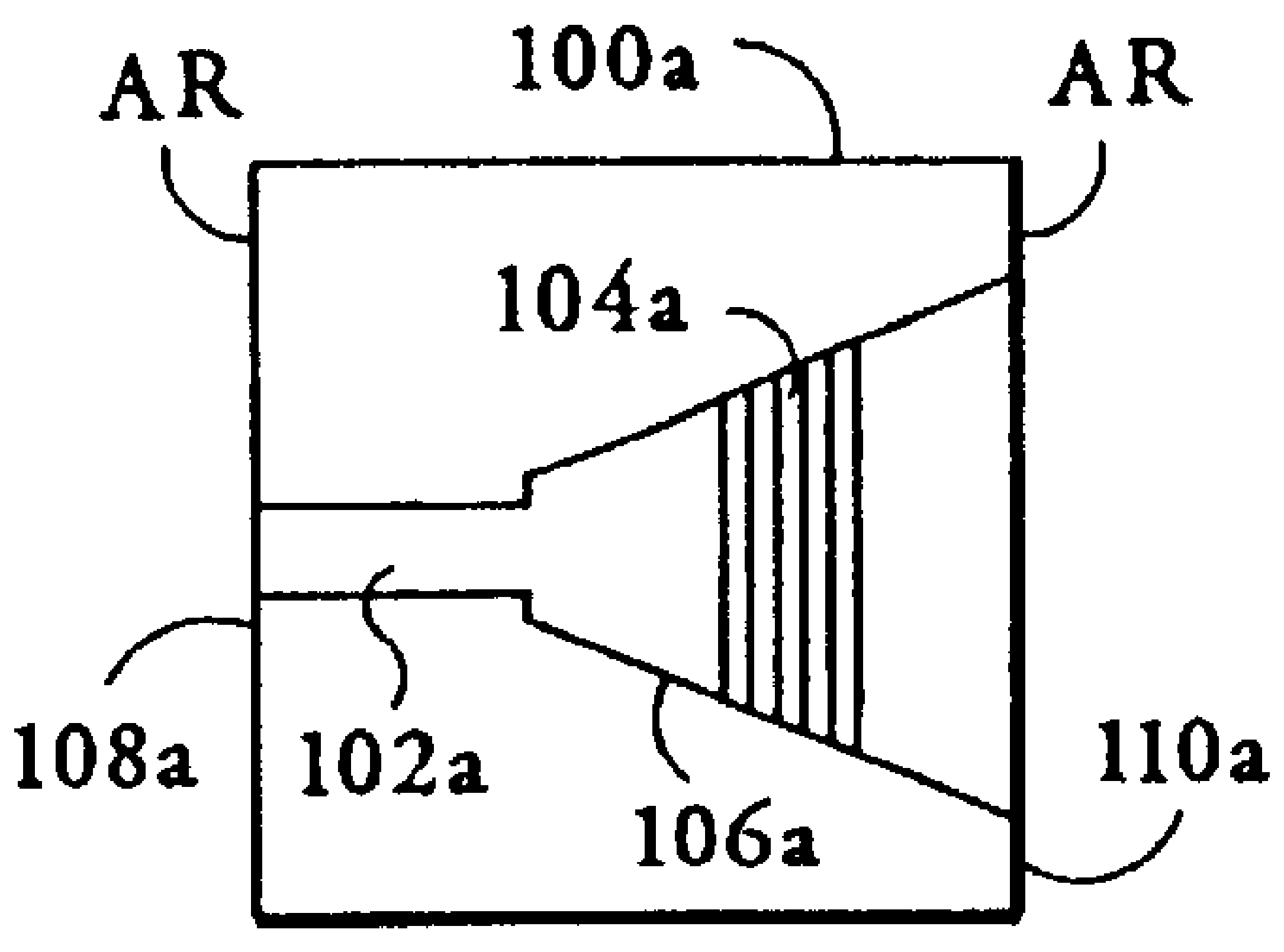
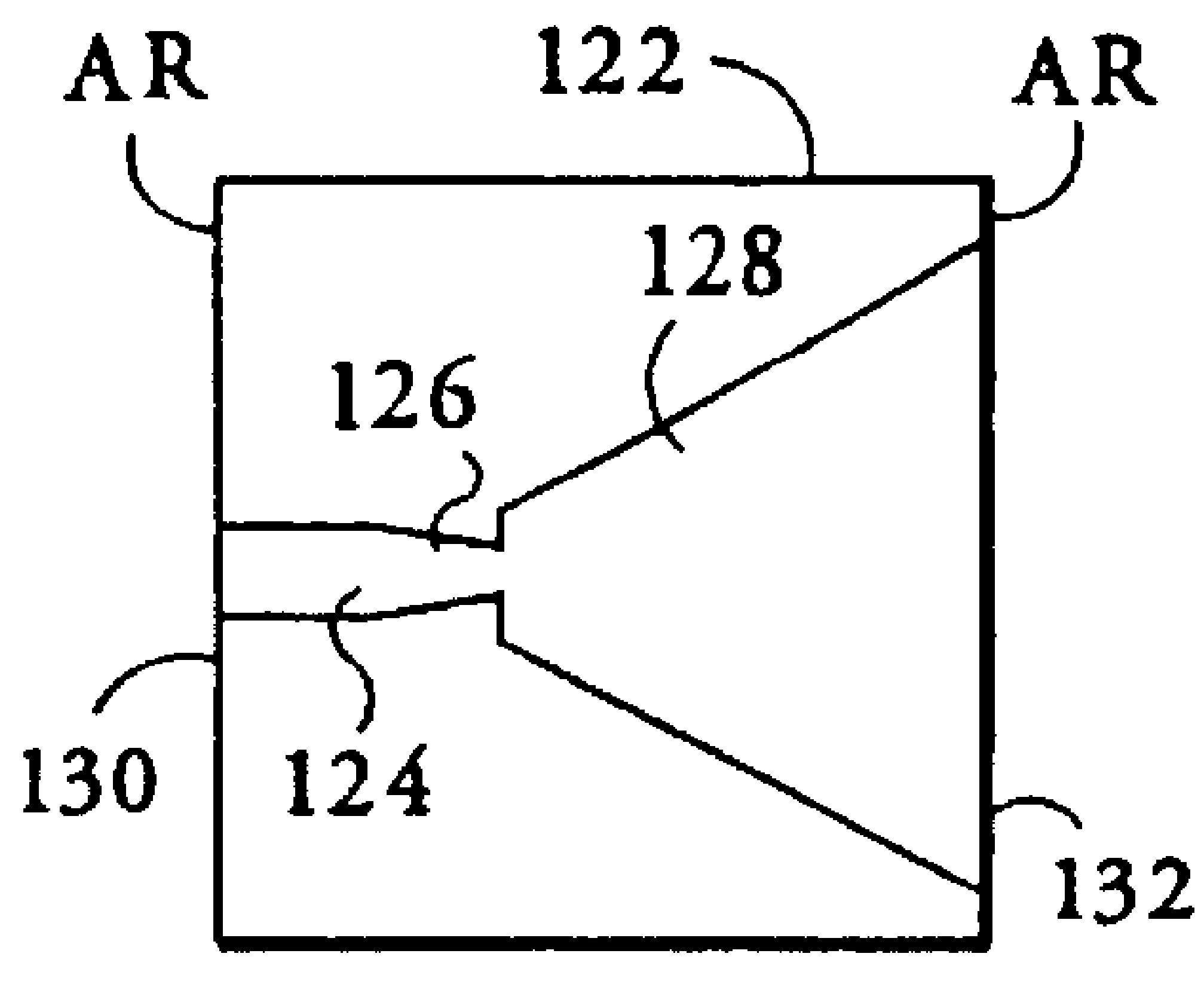


FIG. 6g



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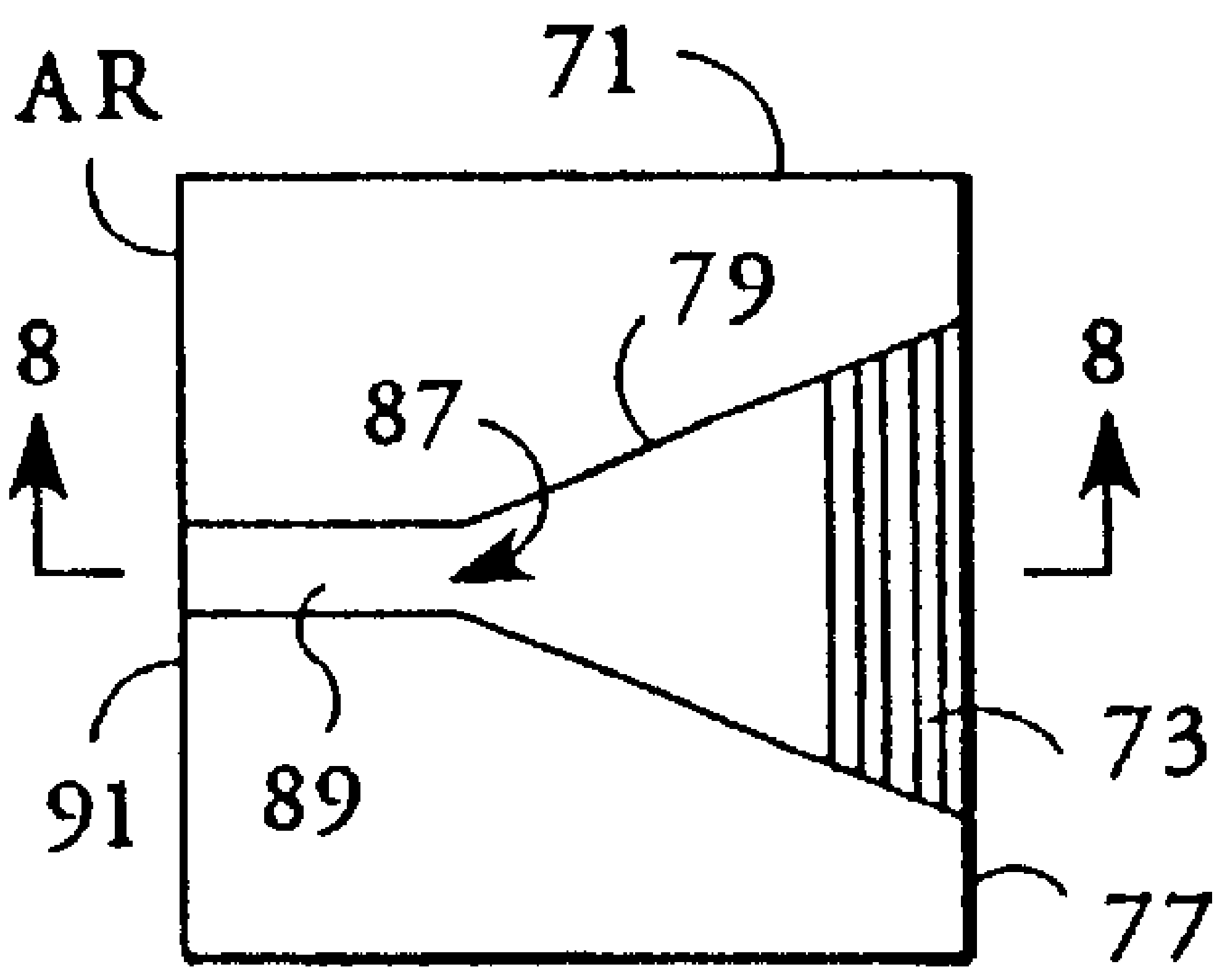

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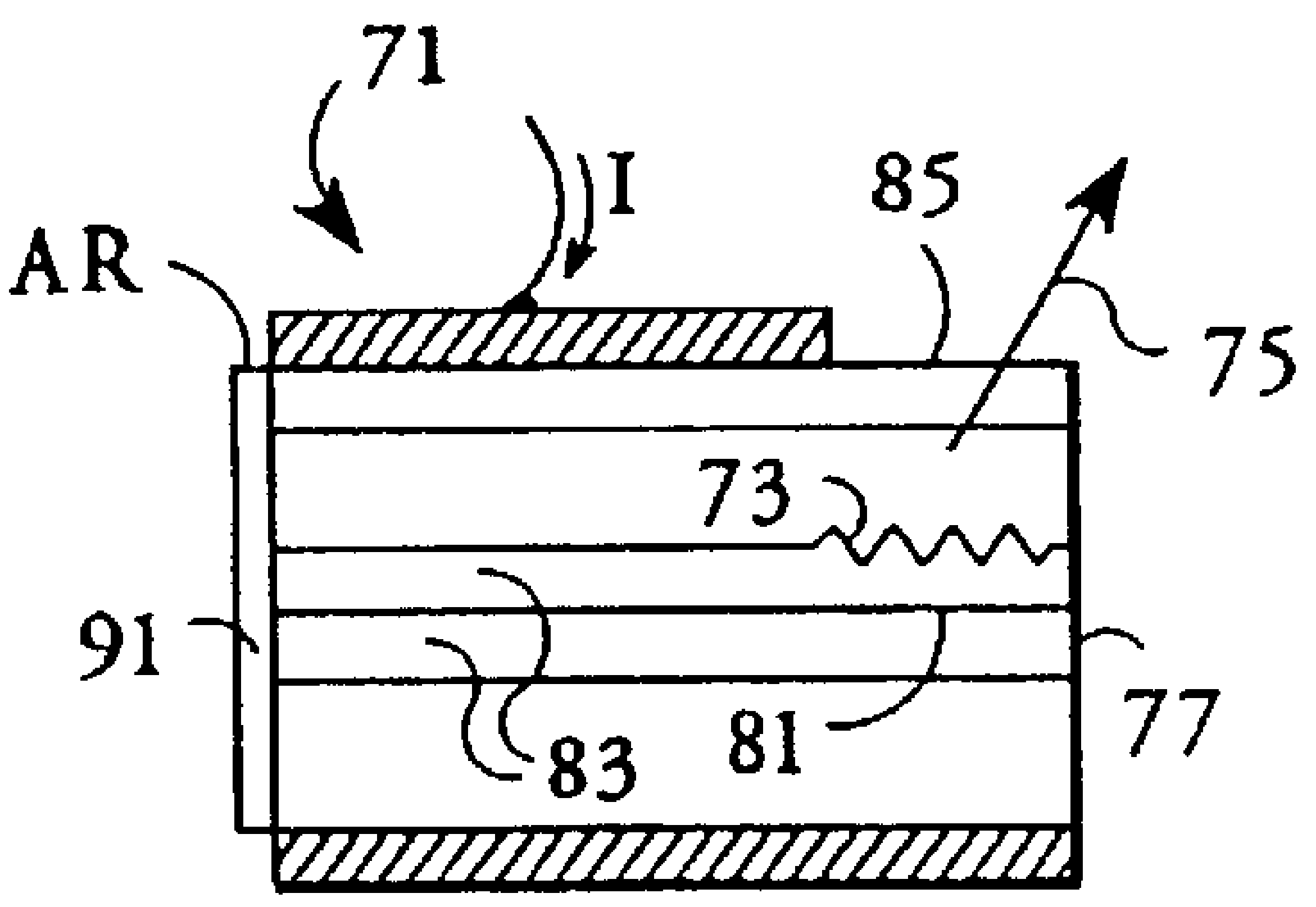
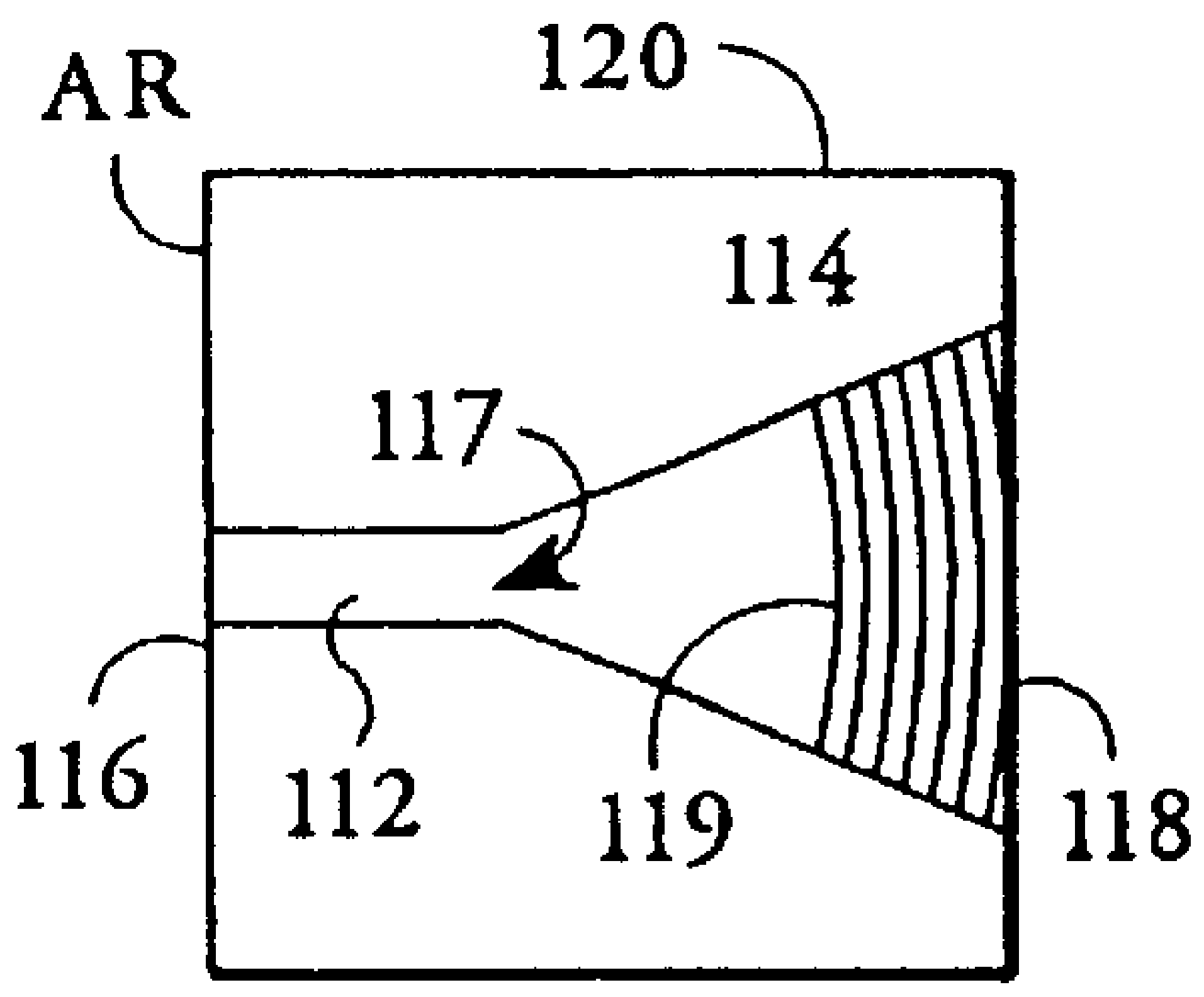


FIG. 8



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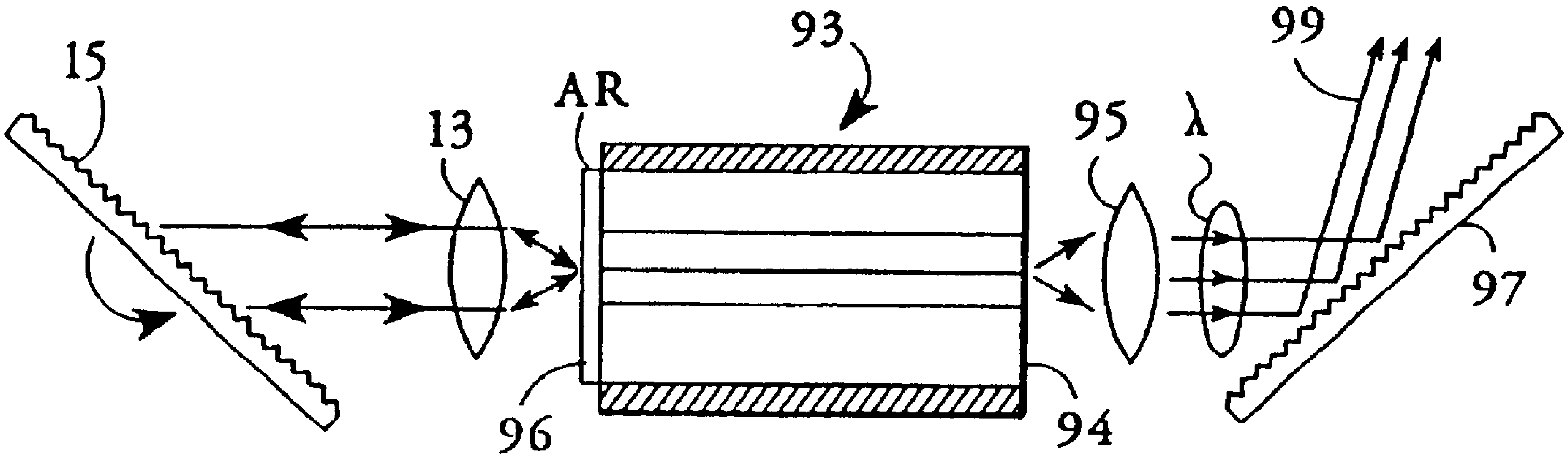

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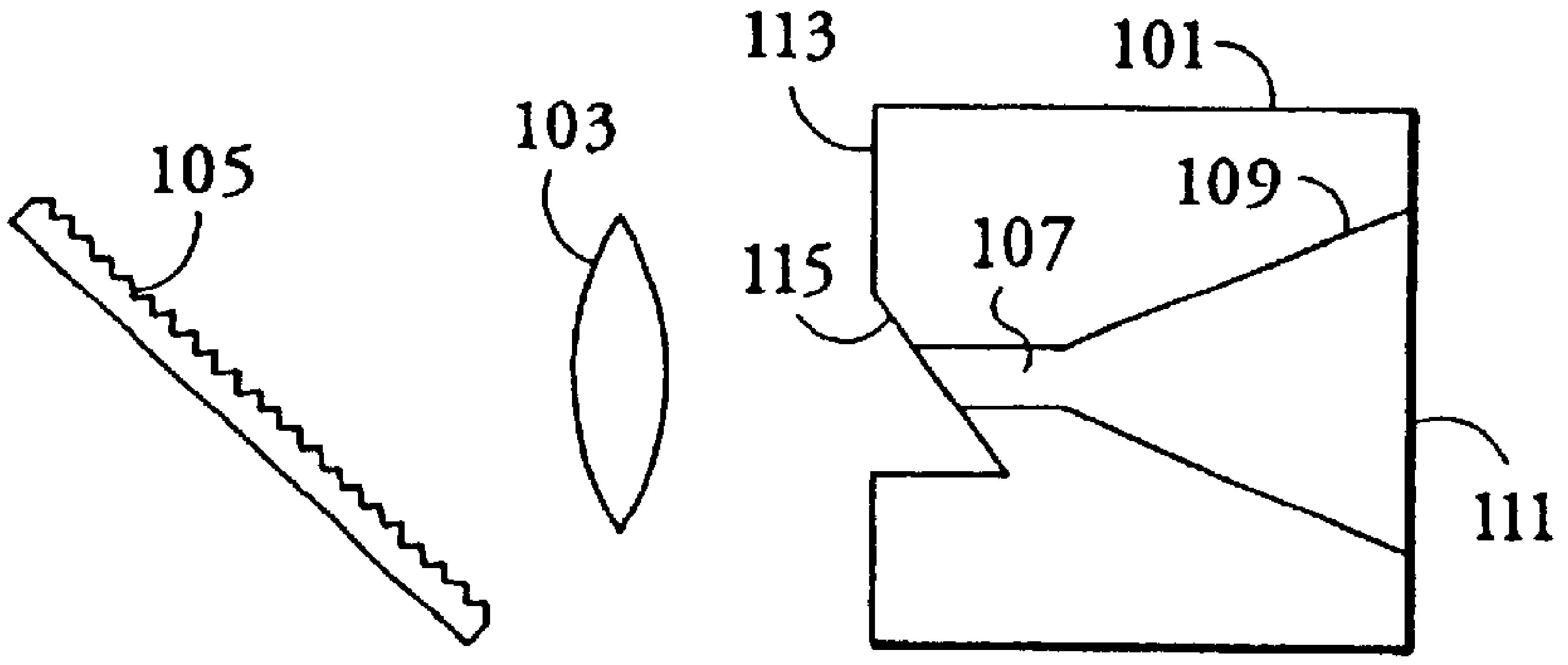

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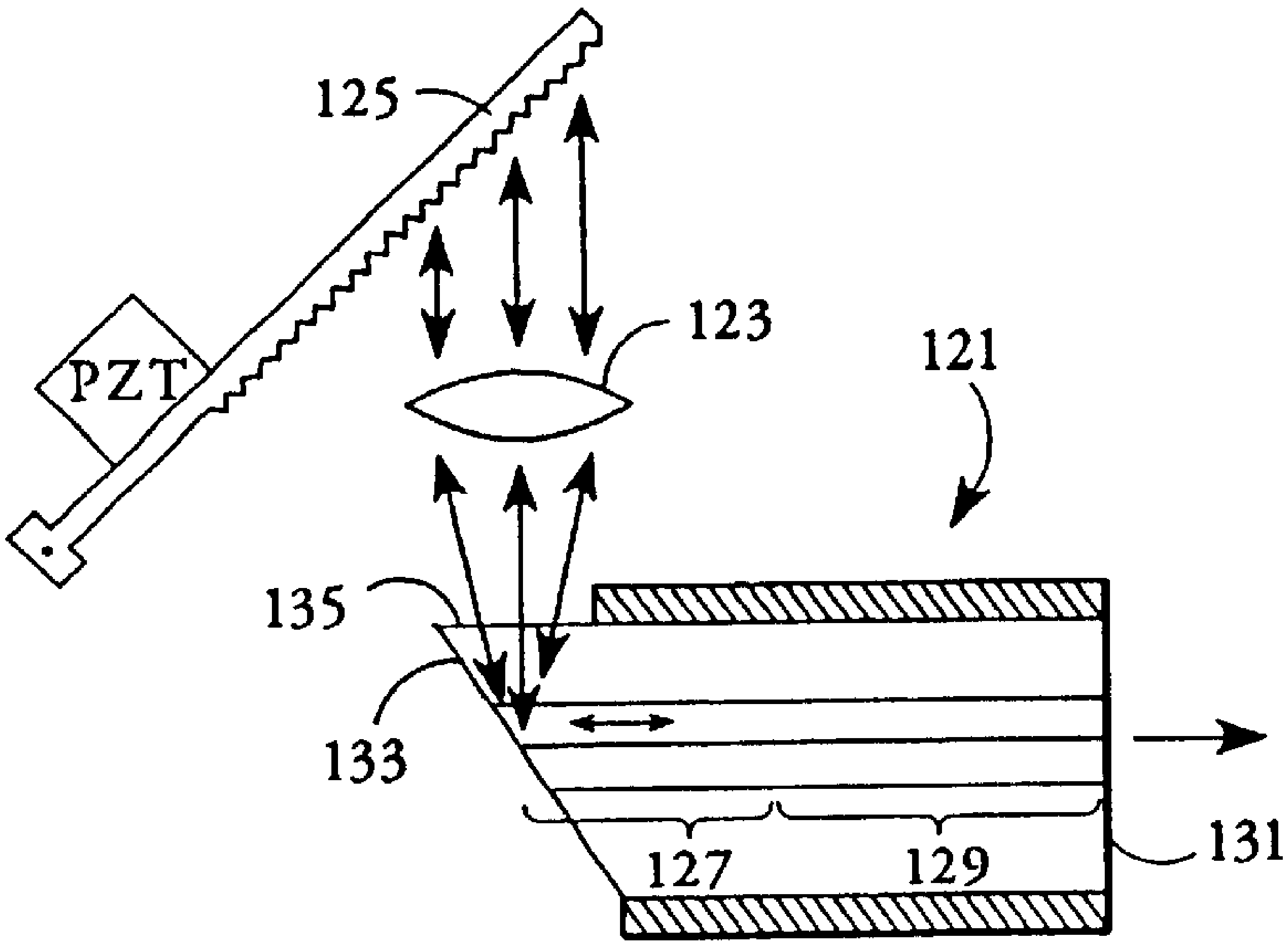


FIG. 12

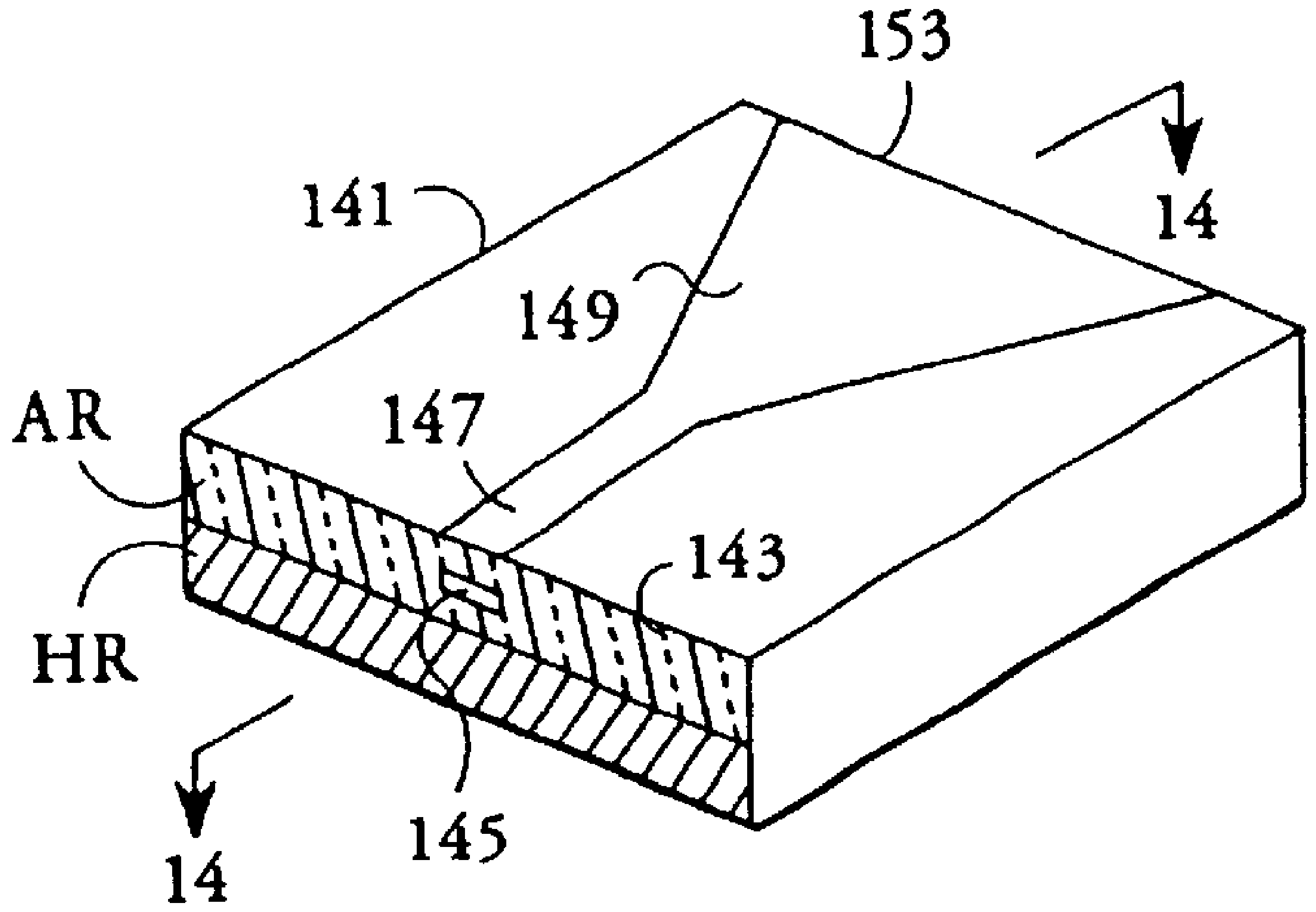


FIG. 13

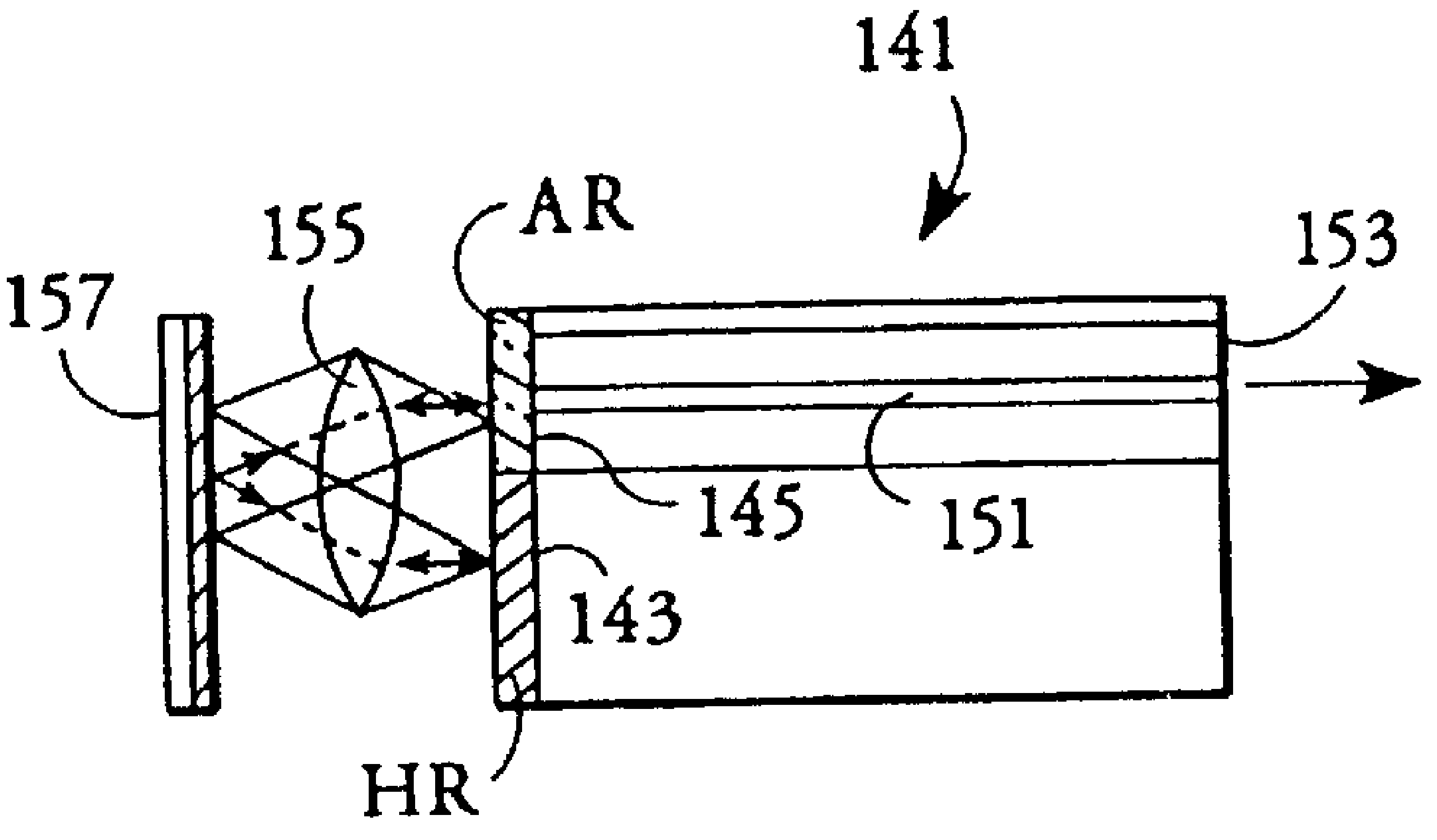


FIG. 14

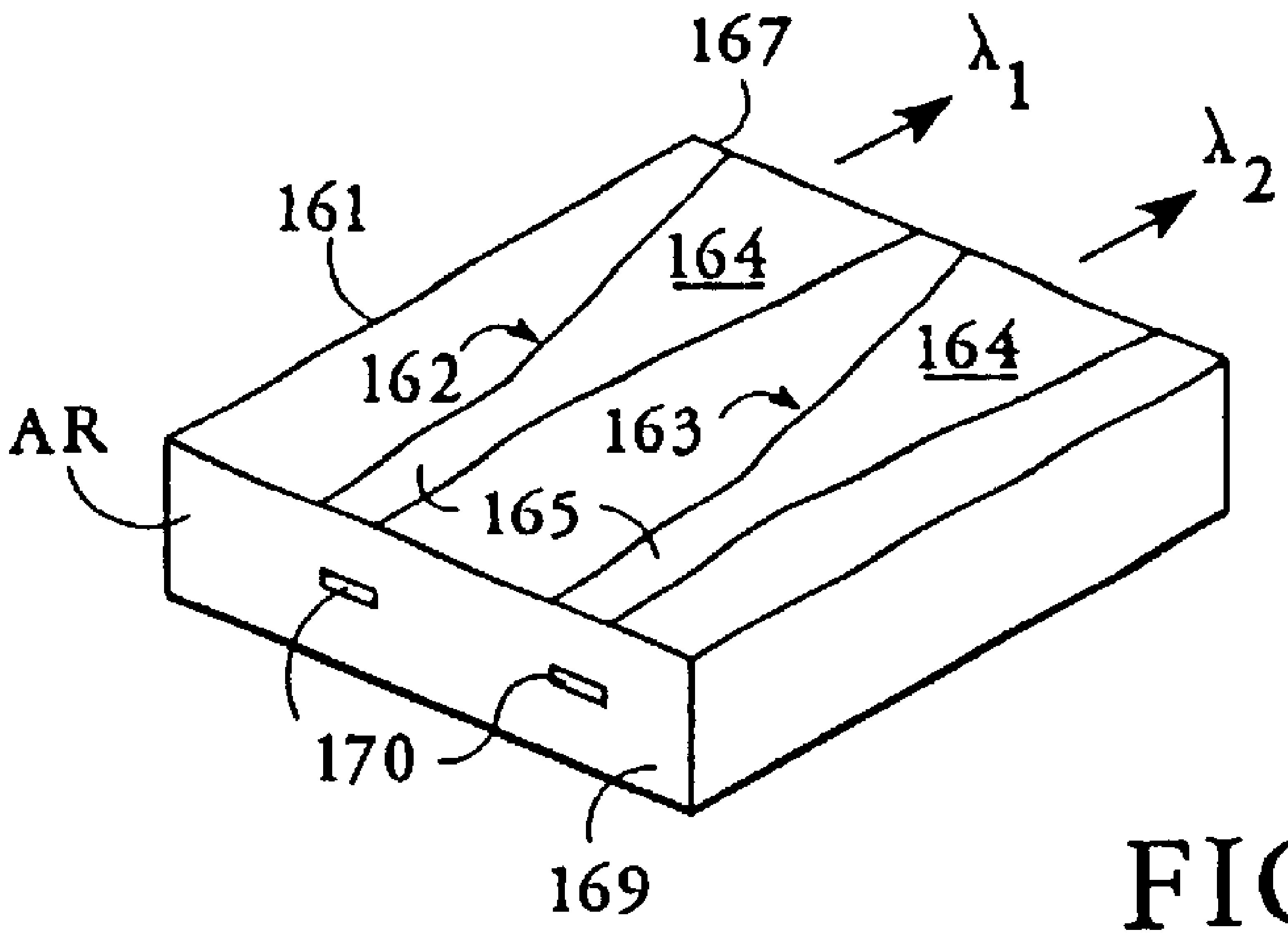


FIG. 15

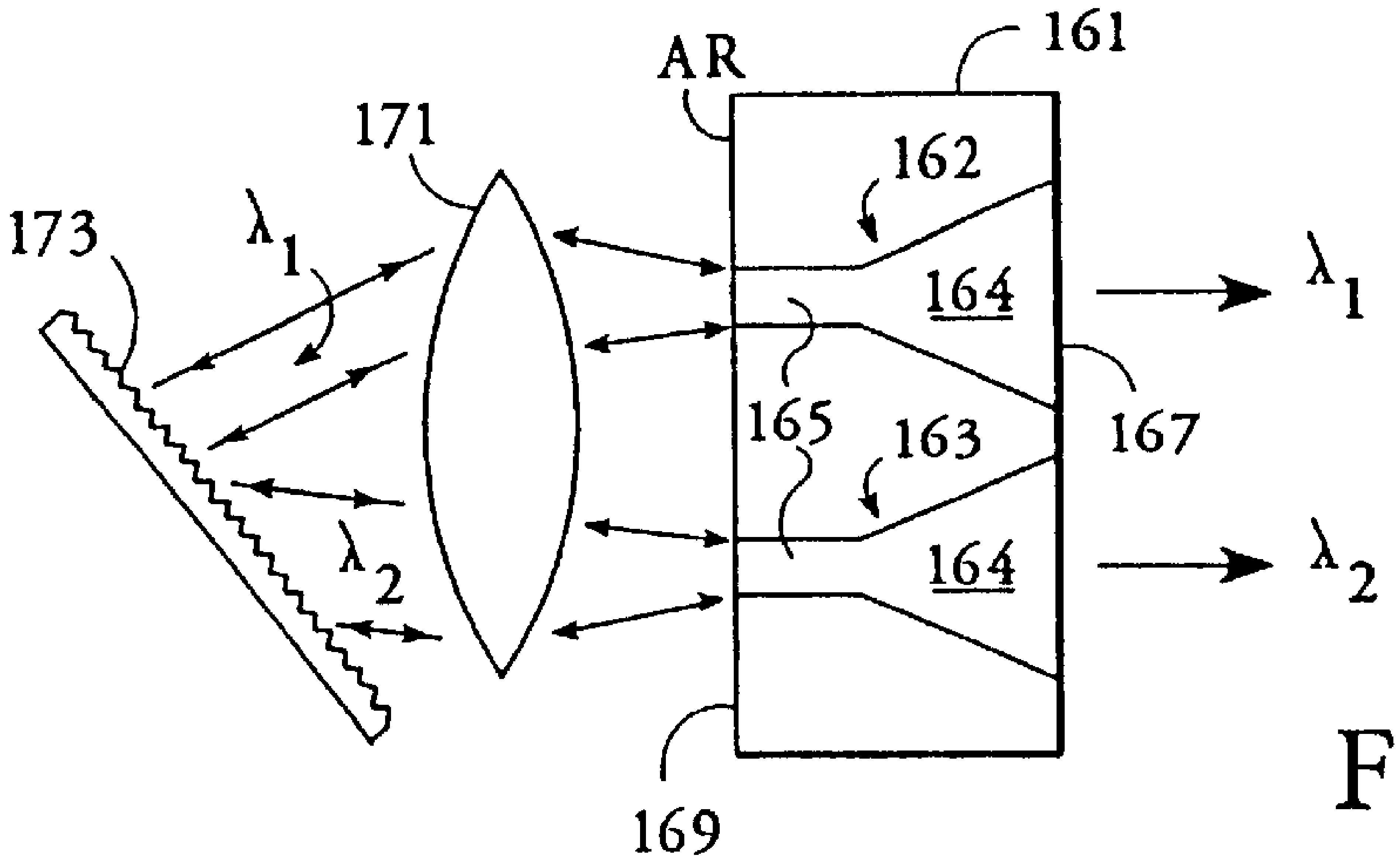


FIG. 16

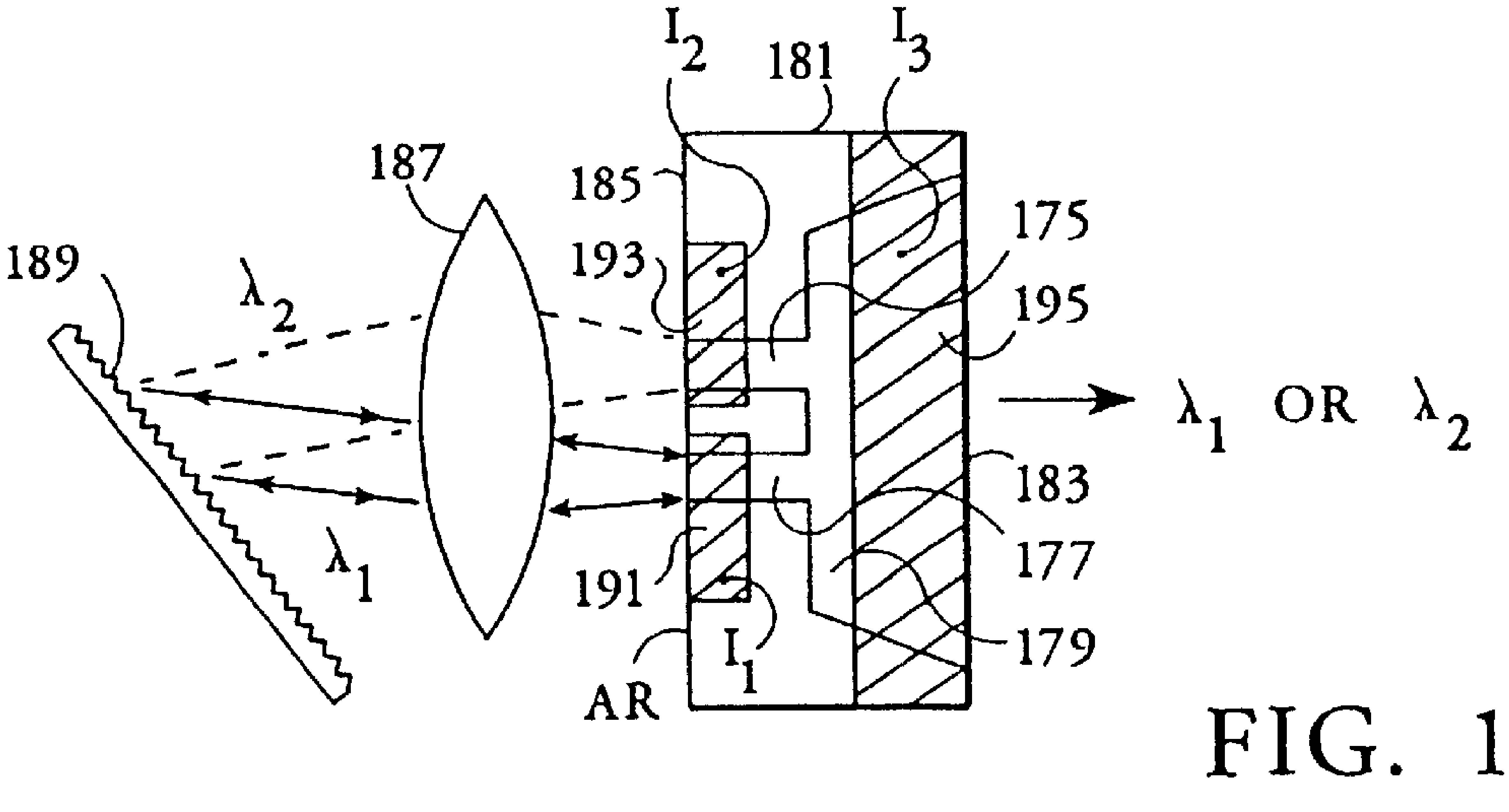
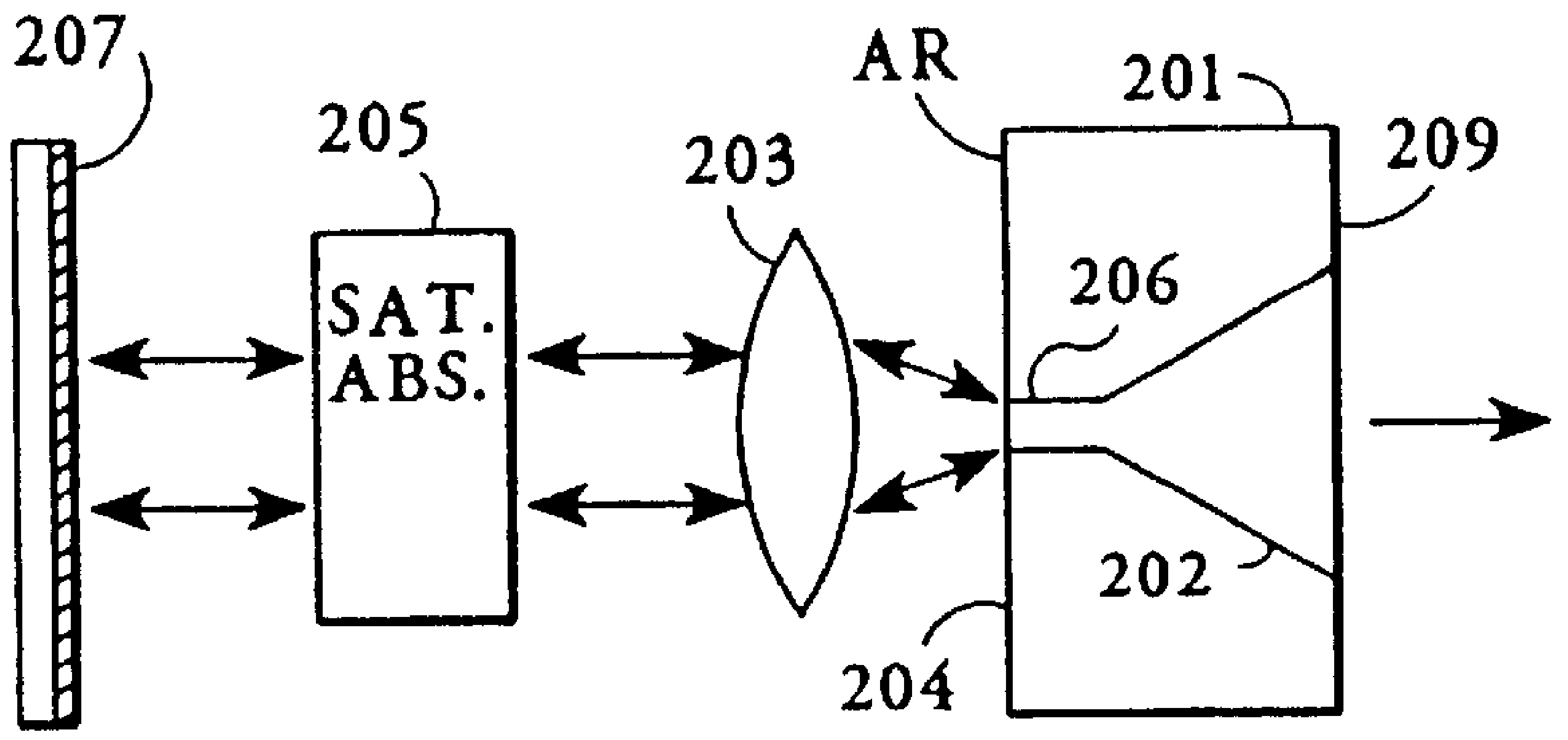


FIG. 17



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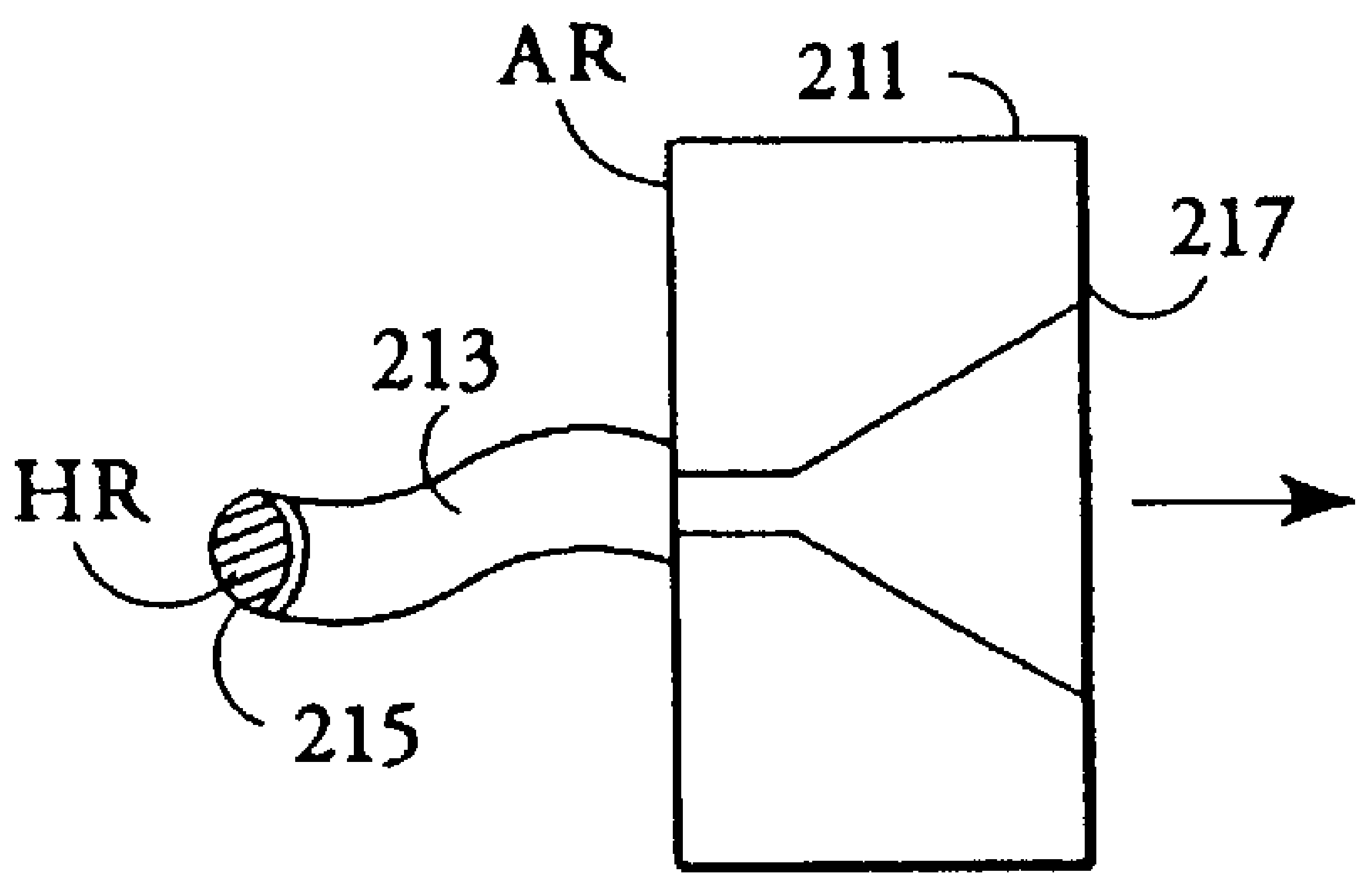


FIG. 19

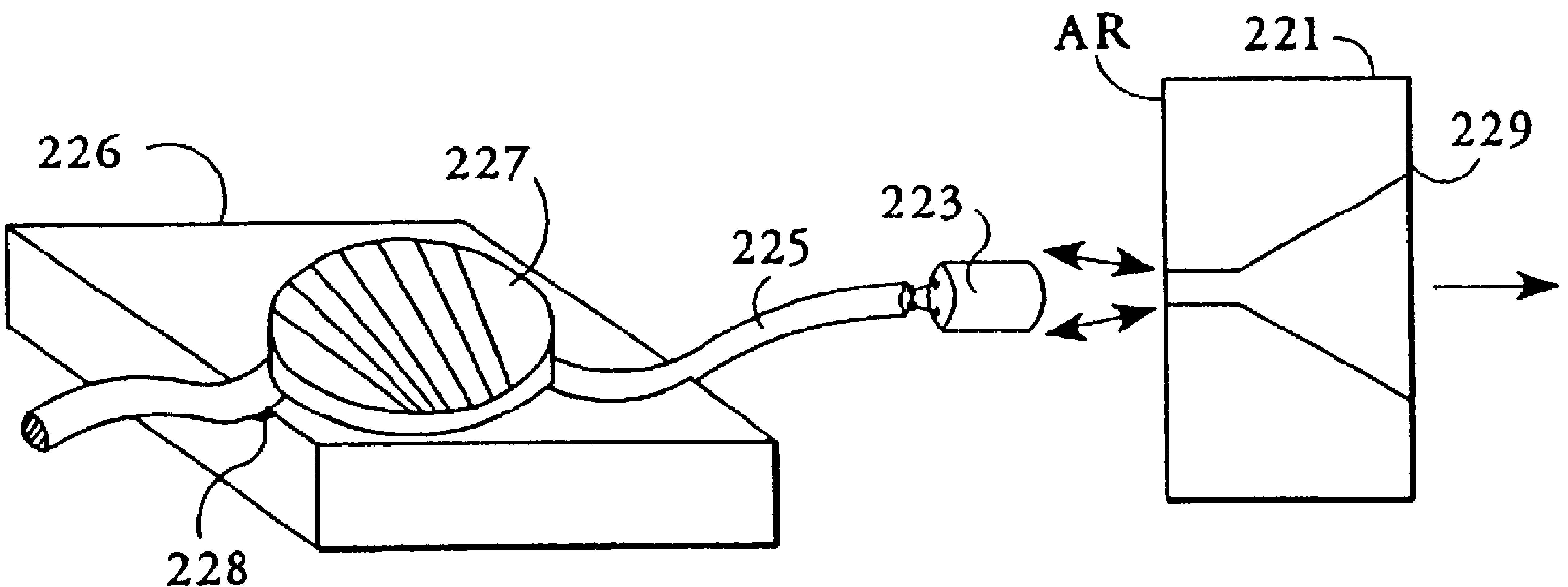


FIG. 20

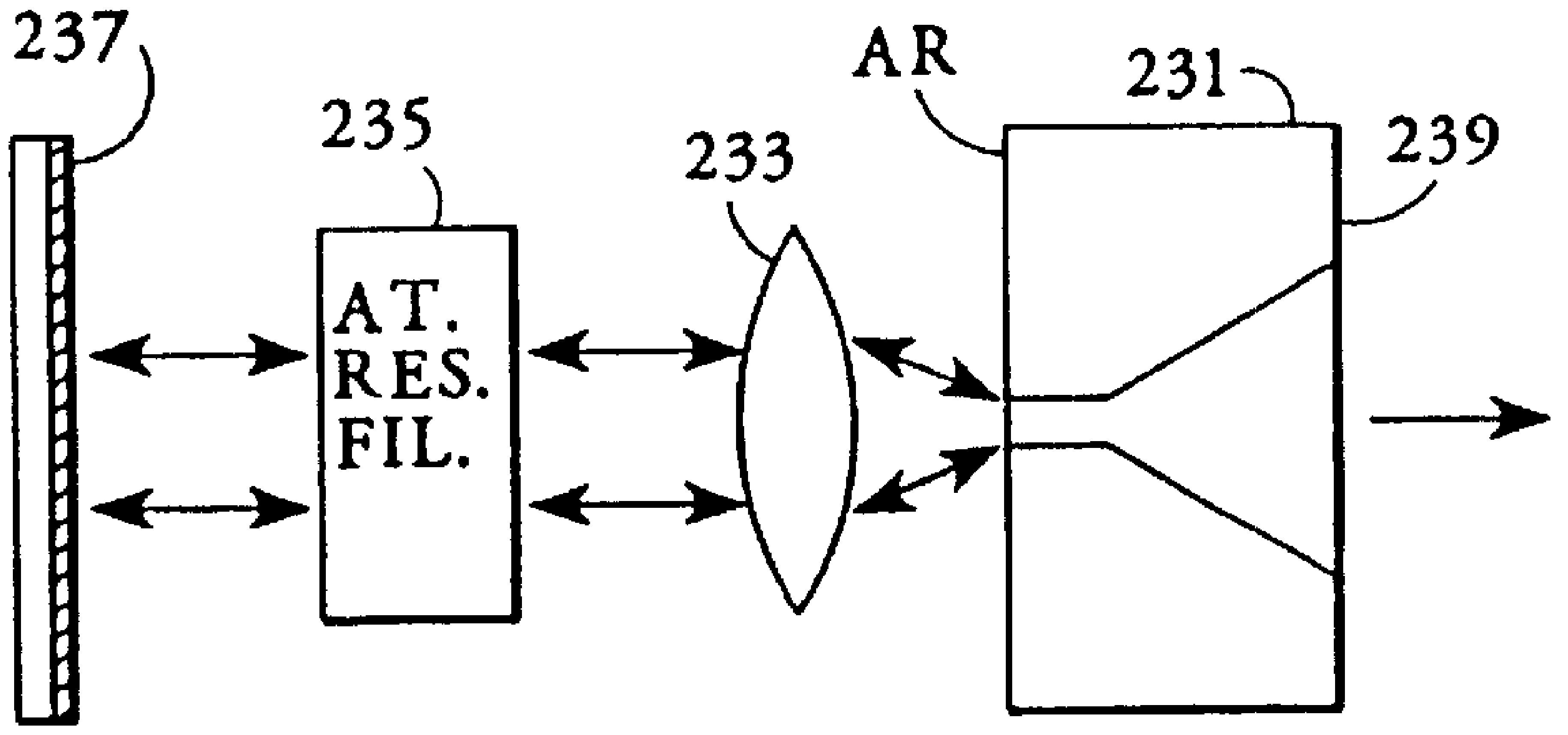


FIG. 21

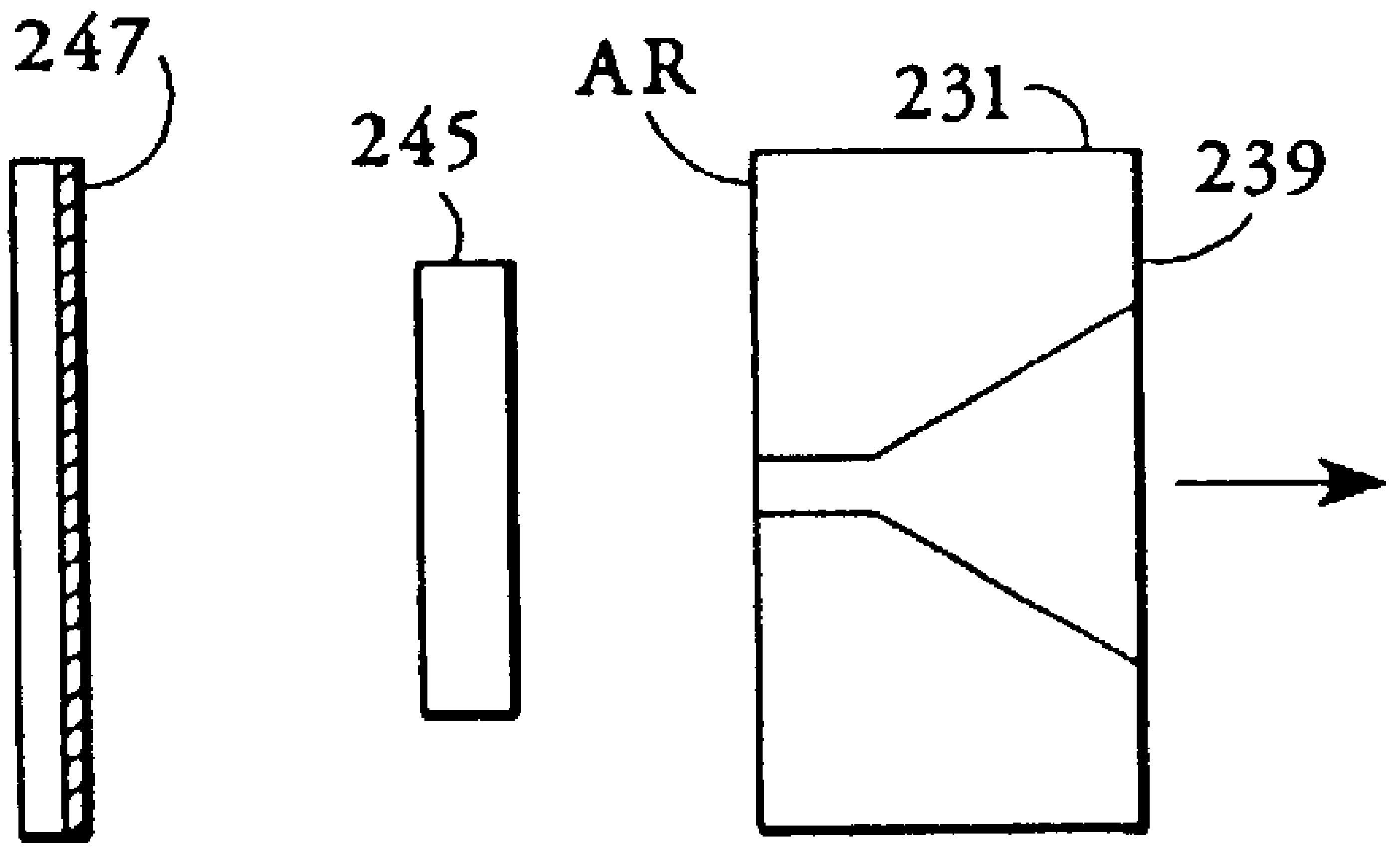
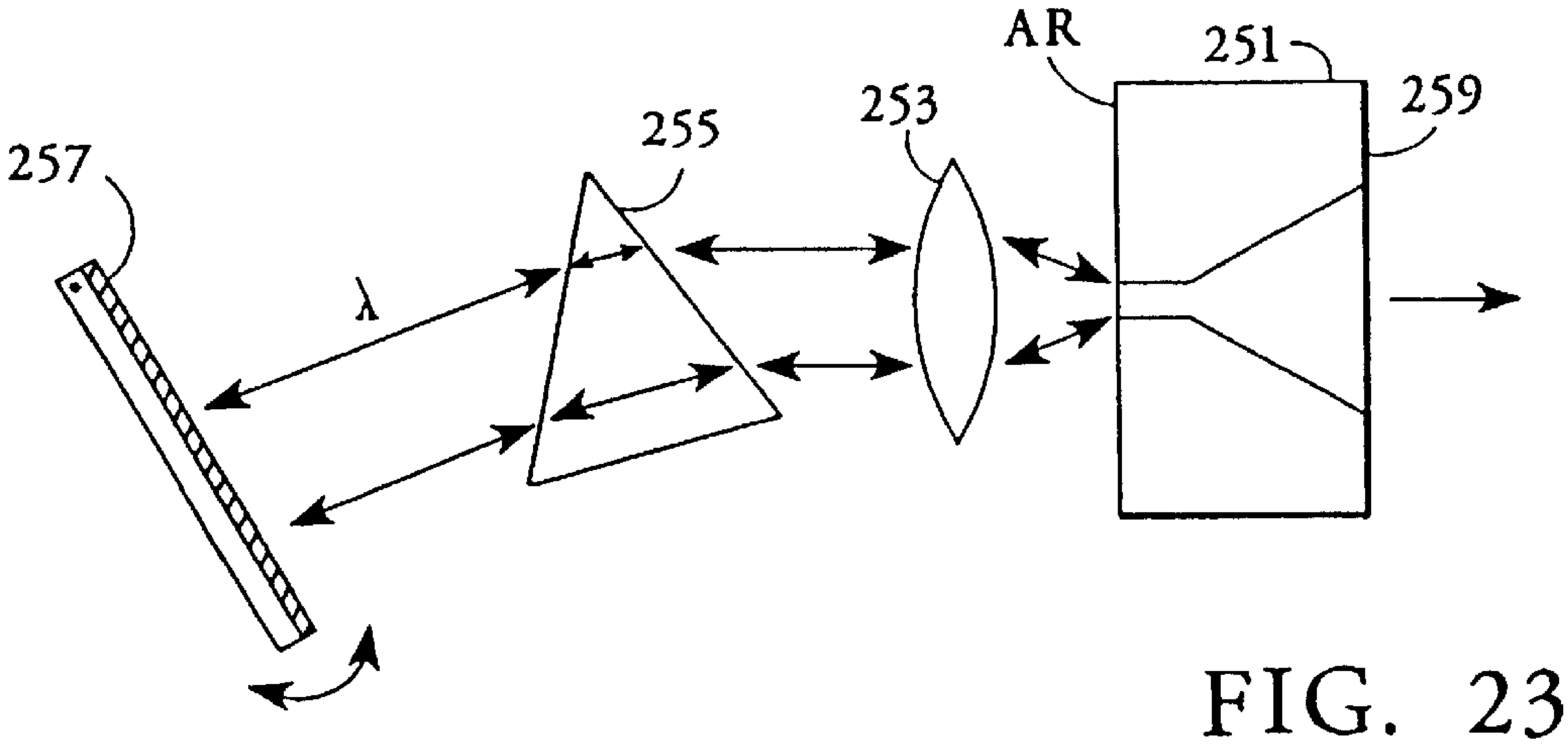


FIG. 22



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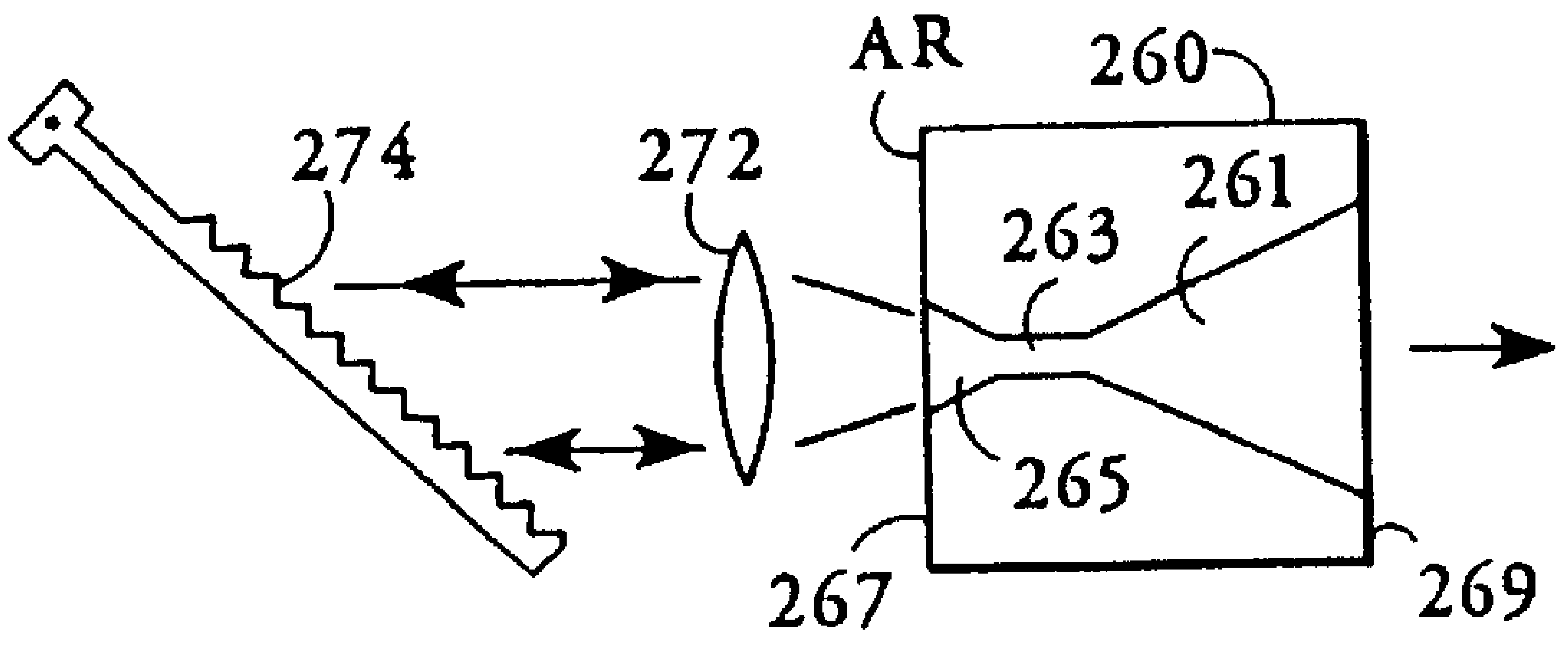


FIG. 24a

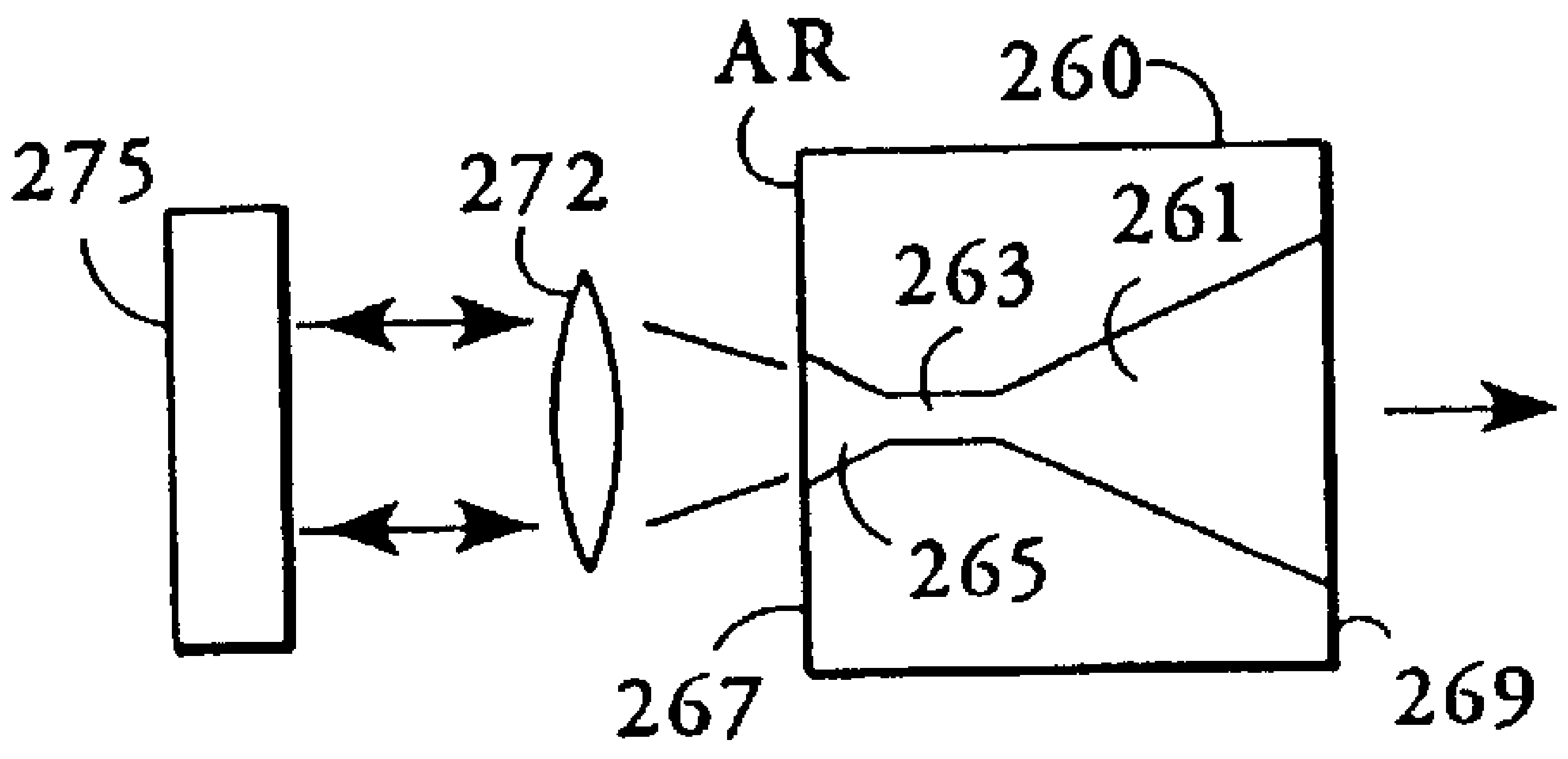
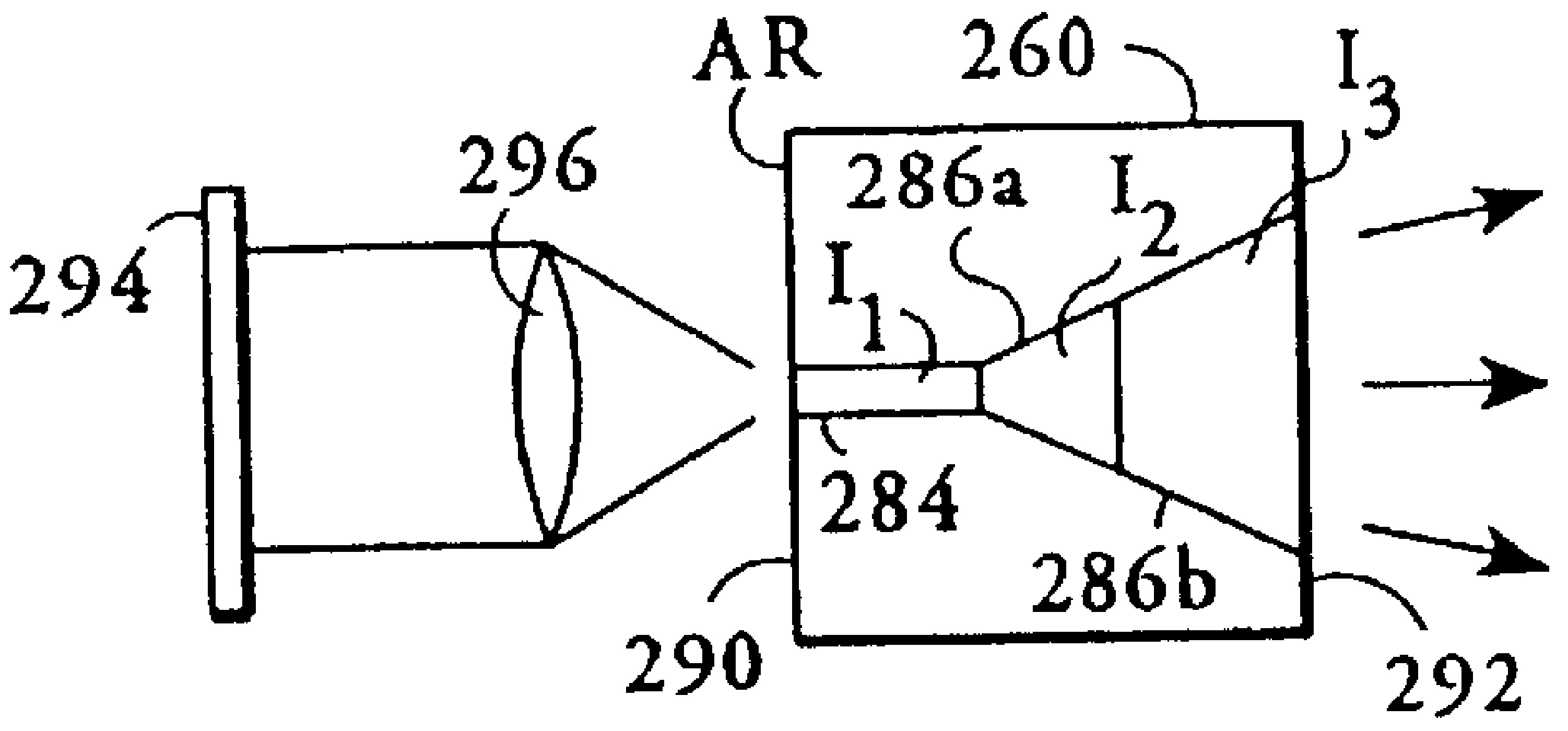


FIG. 24b



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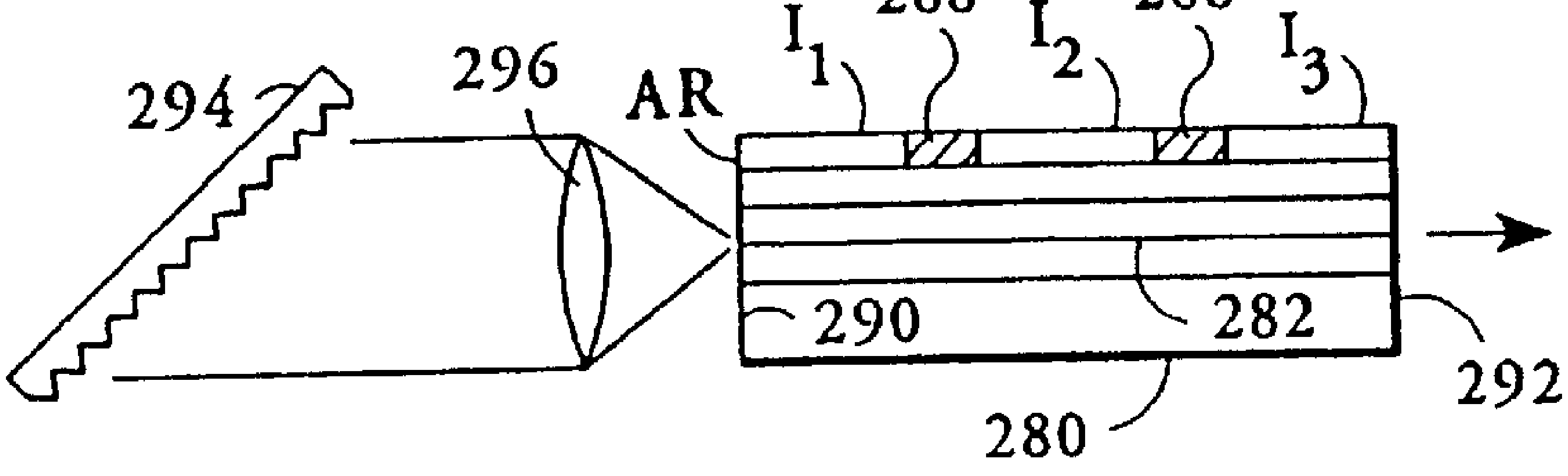

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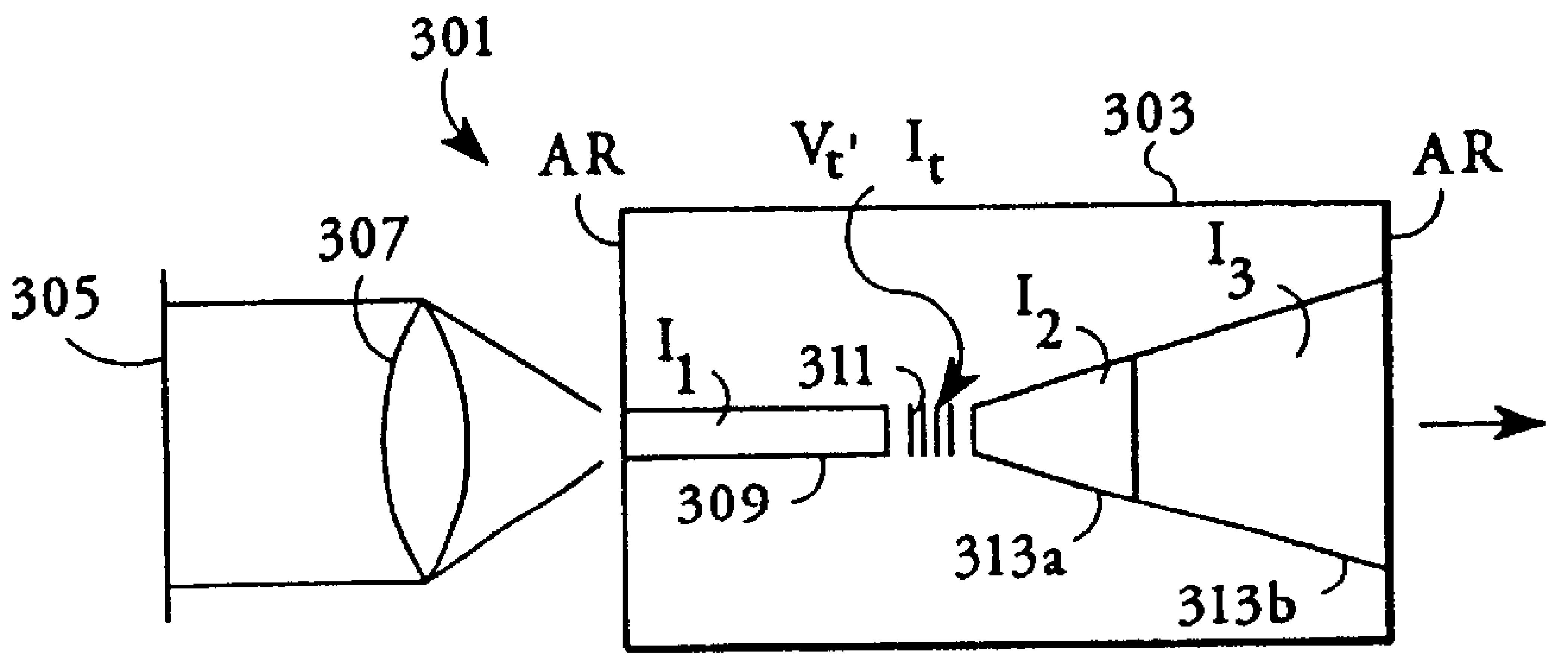
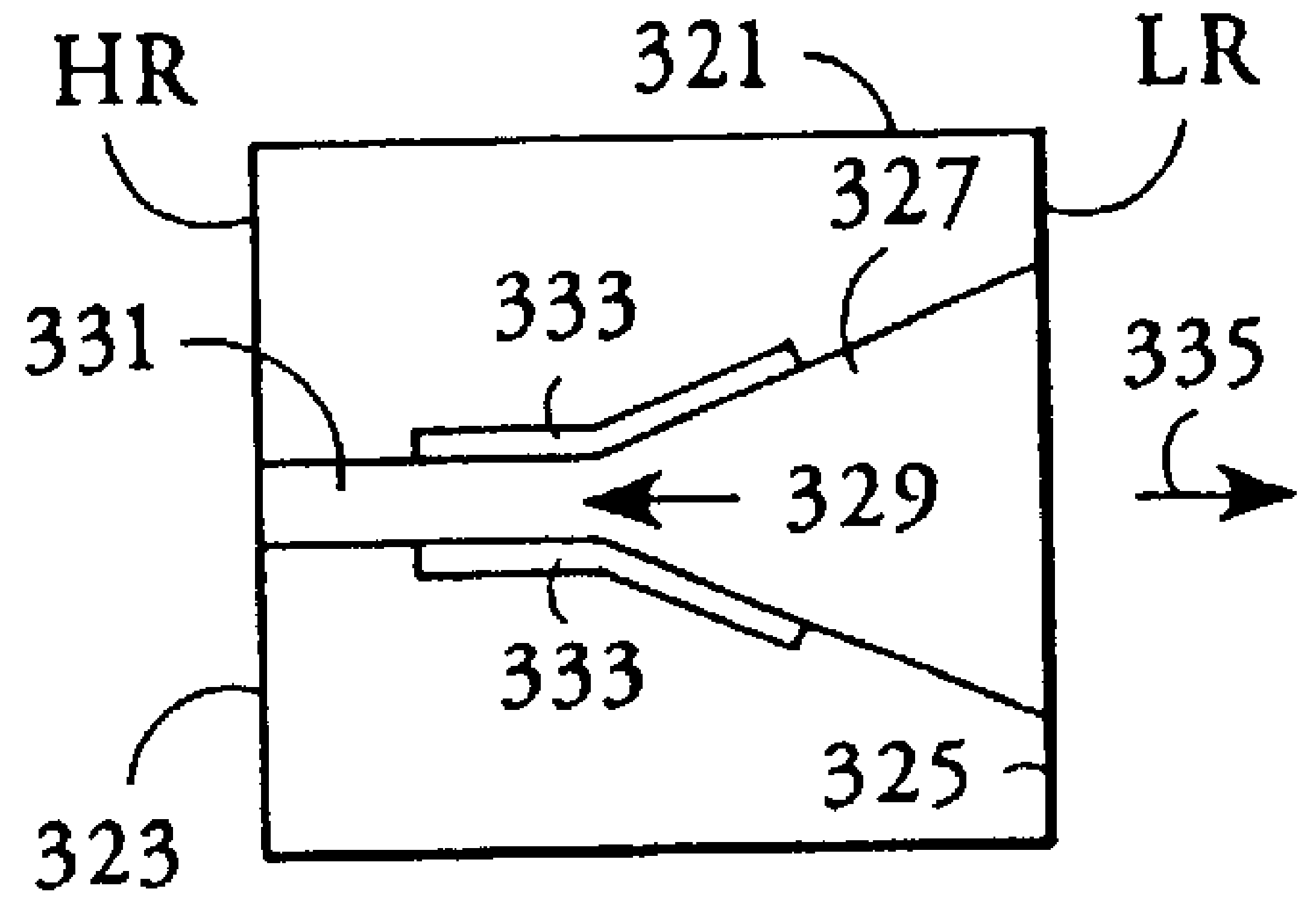


FIG. 26



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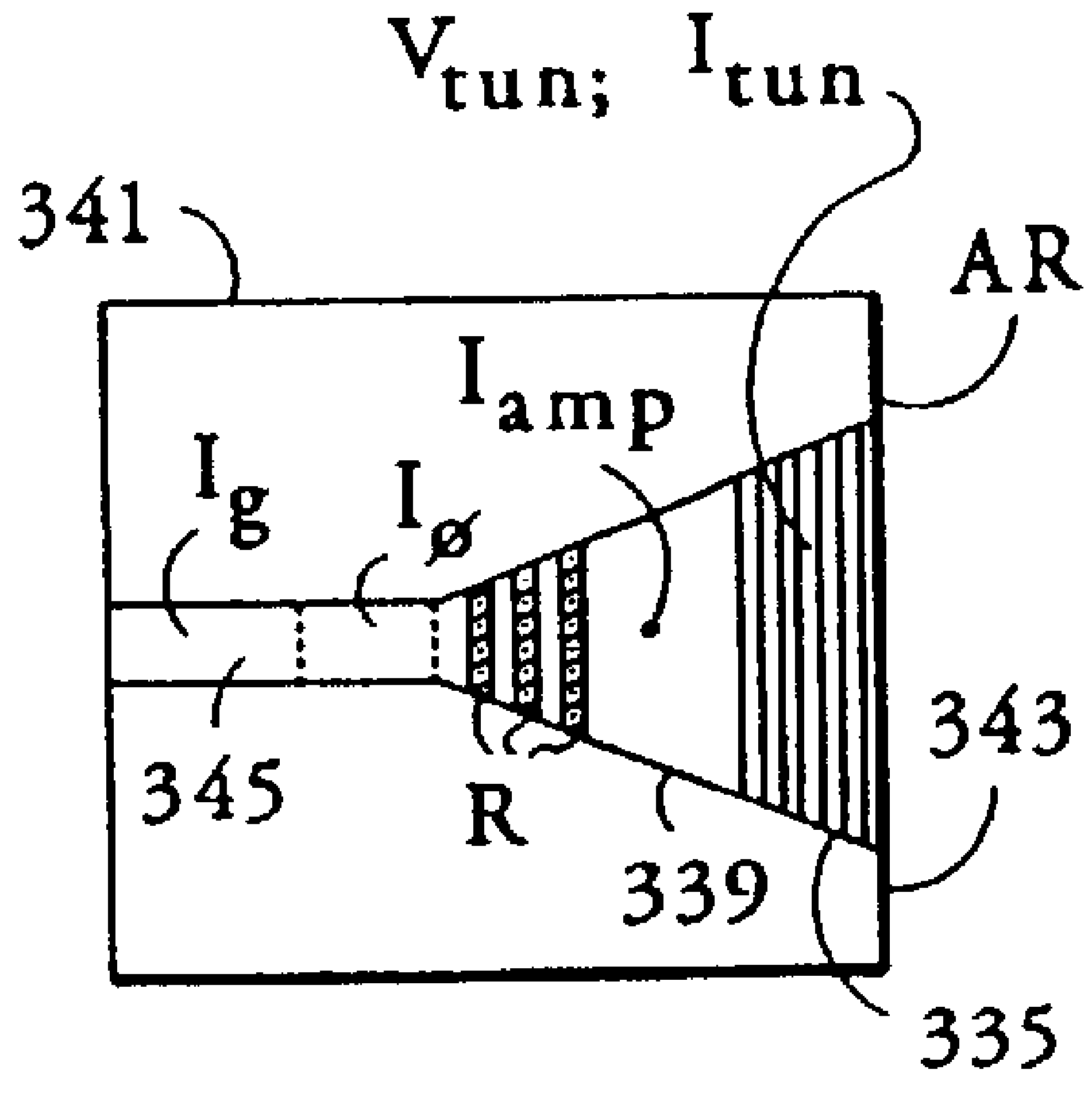
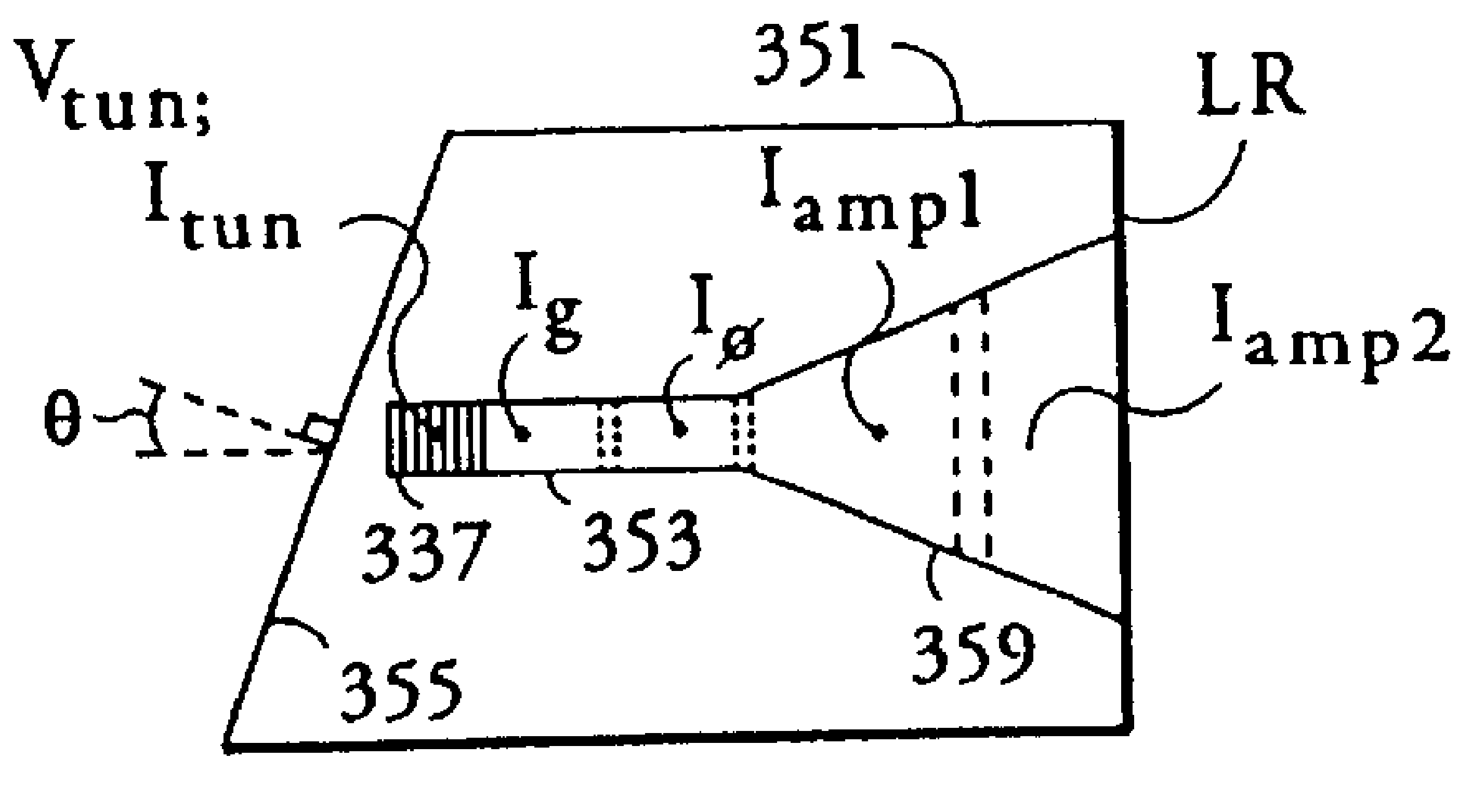


FIG. 29 labels below

FIG. 28



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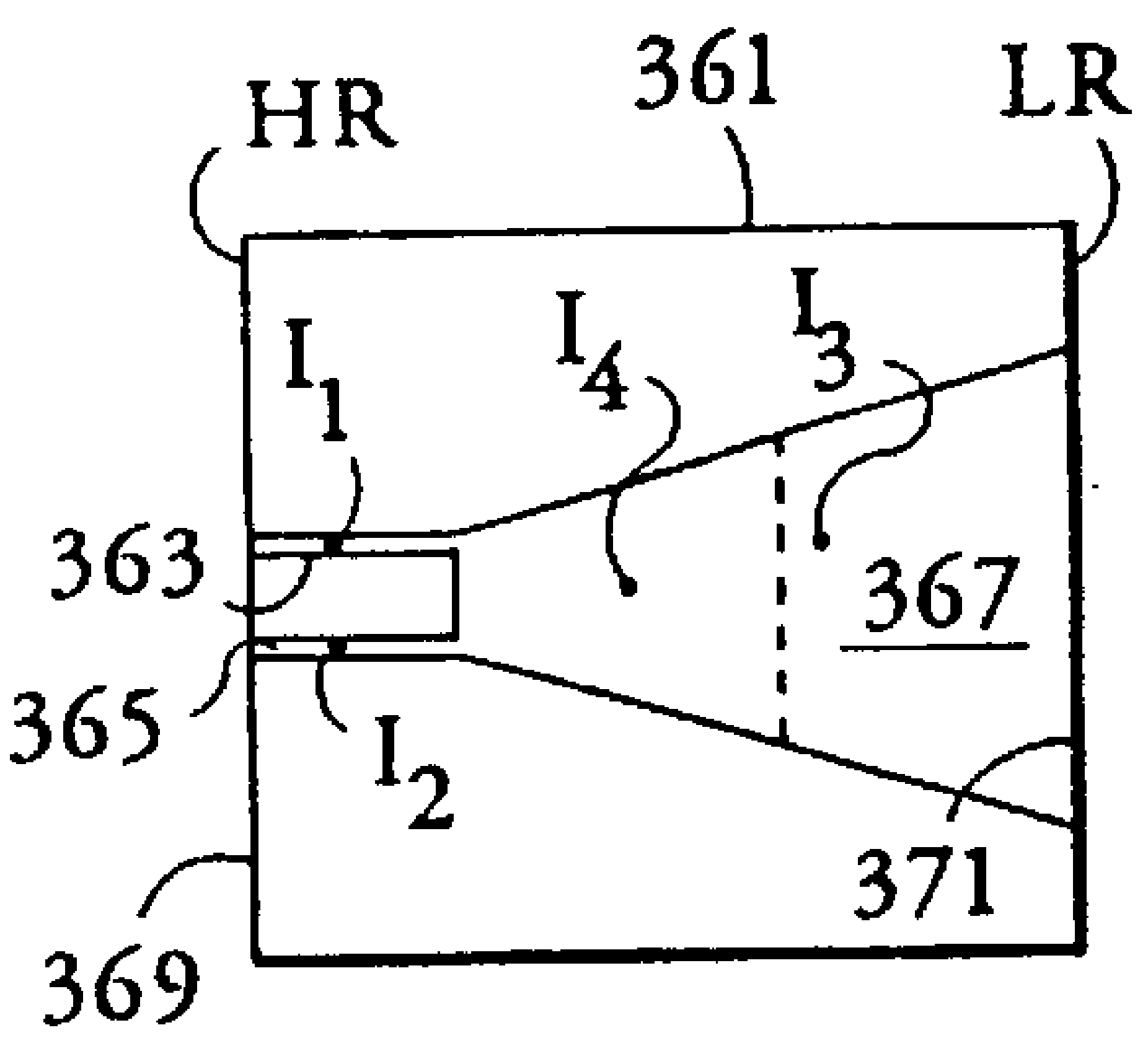

FIG. 30

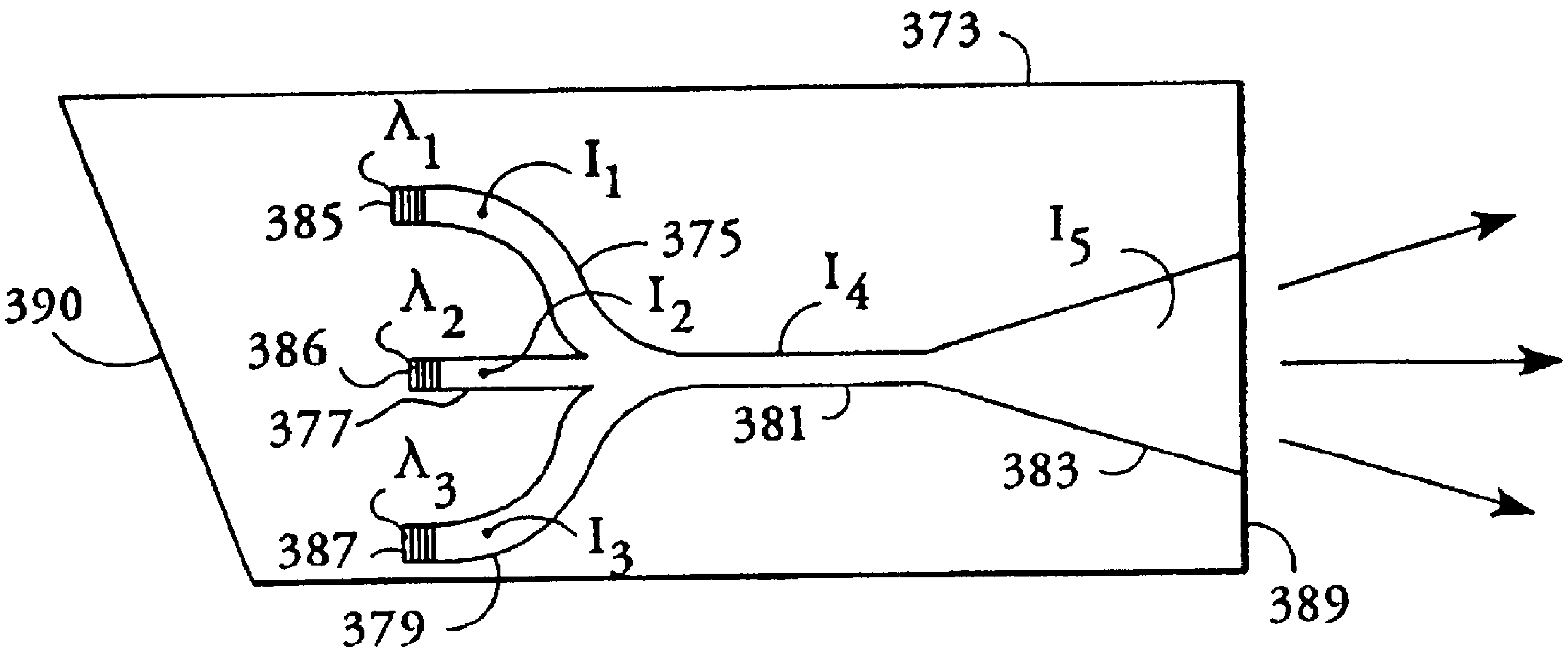
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FIG. 31

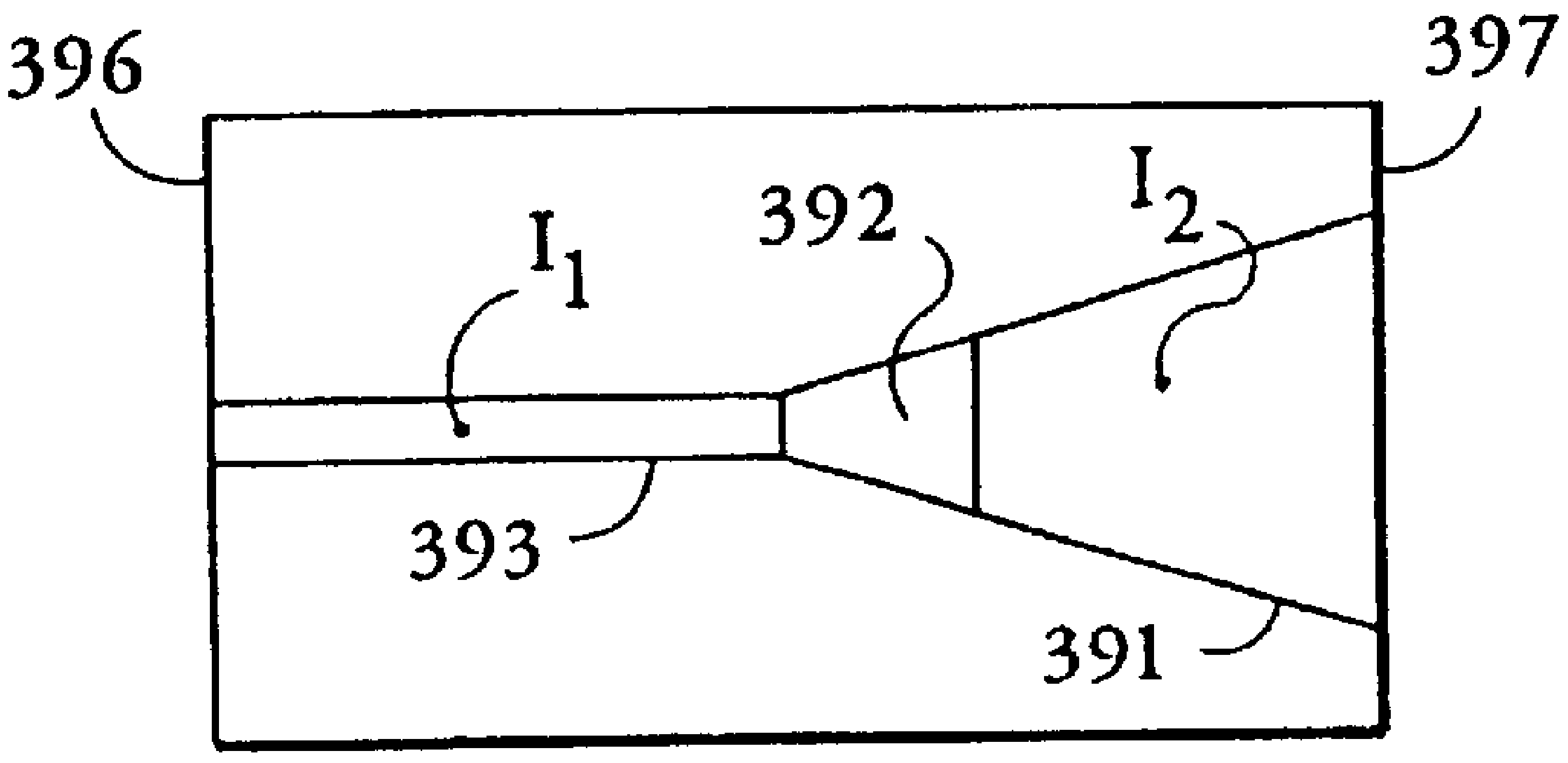
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FIG. 32

SEMICONDUCTOR LASER WITH INTEGRAL SPATIAL MODE FILTER

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

This *is a reissue application of U.S. Pat. No. 5,602,864, which issued from application Ser. No. 08/393,136 filed Feb. 21, 1995, which* is a divisional *application* of application Ser. No. **[**07/263,190**]** *08/263,190* filed on Jun. 21, 1994 *and now U.S. Pat. No. 5,592,503*, which is a divisional application of *application* Ser. No. *08/*001,735 filed Jan. 7, 1993 *and* now U.S. Pat. No. 5,392,308.

TECHNICAL FIELD

The present invention relates to external-cavity semiconductor lasers, especially to those laser that include a frequency-selective tuning element for broadband tunability and narrow linewidth light emission. The invention also relates to lasers with single spatial mode, diffraction-limited emission, and to light amplifying diode heterostructures with flared gain regions.

BACKGROUND ART

External-cavity semiconductor lasers, including lasers with frequency selective tuning elements in the cavity, are well known and have been extensively studied. For example, T. Fujita, et al., in Applied Physics Letters 51(6), pages 392–394 (1987), describe a laser having a buried heterostructure laser that has been antireflection (AR) coated on the intracavity facet, a collimating lens, a polarization beamsplitter, external cavity mirrors in each of the TE and TM polarization light paths, and an electro-optic modulator in the TE polarization path between the beamsplitter and cavity mirror. The configuration allows selection of either the TE or TM mode of oscillation by adjusting the modulator's bias voltage. W. Sorin, et al., in Optics Letters 13(9), pages 731–733 (1988), describe a laser having a laser diode with one of its facets AR coated to reduce its reflectivity, a lens, a single mode optical fiber and a tunable evanescent grating reflector for providing feedback. The laser is wavelength tunable by sliding the feedback grating laterally over the fiber. P. Zorbedian et al., in Optics Letters 13(10), pages 826–828 (1988), describe another wavelength tunable laser using either a rotatable interference filter in an external Fabry-Perot cavity or an external grating reflector providing frequency-selective feedback.

A problem with previously available external-cavity semiconductor lasers is their generally low output power (on the order of 10 mW cw and 200–300 mW pulsed). Further, higher output powers are associated with unstable output intensity and frequency and less than good modal quality.

In U.S. Pat. No. 4,251,780, Scifres et al. describe semiconductor injection lasers that are provided with a stripe offset geometry in order to enhance and stabilize operation in the lowest order or fundamental transverse mode. In one configuration, the stripe geometry has a horn shaped or trapezoidal section connected to a straight section, in which the width of the horn shaped or trapezoidal section expands from 8 μm at the straight section to 25 μm at the cleaved end facet. In contrast to configurations in which the edges of the stripe waveguides are linear and orthogonal to the cleaved end facets of the lasers, the nonorthogonal angled or curved edges of the offset stripe geometries cause higher order modes to reflect or radiate out of the waveguide, thereby increasing the threshold of the higher order modes relative to the fundamental mode.

In U.S. Pat. No. 4,815,084, Scifres et al. describe semiconductor lasers and laser arrays in which lenses and other optical elements have been integrated into the semiconductor bodies of the lasers by means of refractive index changes at boundaries in the light guiding region, where the boundaries are characterized by a lateral geometric contour corresponding to surfaces of selected optical elements so as to cause changes in shape of phase fronts of lightwaves propagating across the boundaries in a manner analogous to the change produced by the optical elements. In one embodiment, a biconcave or plano-concave diverging lens element is integrated within the laser in order to counteract the self-focusing that usually occurs in broad area lasers and that can lead to optical filamentation and lateral incoherence across the laser. The diverging lens in the laser allows the laser to operate as an unstable resonator, leading to high output power and good coherence across the lateral wavefront.

An object of the invention is to provide a high power, external cavity, semiconductor laser which emits a single spatial mode, diffraction-limited output beam.

Another object of the invention is to provide a wavelength tunable, high power, external cavity, semiconductor laser with a stable, single frequency, narrow linewidth light output.

DISCLOSURE OF THE INVENTION

The above objects are met with a laser in which a semiconductor active medium is located within an at most marginally stable resonant cavity with a single-spatial-mode filter therein. The semiconductor active medium is preferably an electrically pumped light amplifying diode heterostructure or "amplifier chip" that has a flared gain region with a narrow, single mode, optical aperture end and a broad light output end. The flared gain region permits the light to freely diffract as it propagates in the gain region, so the light has a diverging phase front. Only the central-most light rays of backward propagating light can pass through the narrow aperture end of the flared gain region to reach an external rear reflector of the resonant cavity. Rear reflectors integral with the diode heterostructure could also be used. The rear reflector can be a mirror surface or a frequency selective grating reflector. Orientation of the grating reflector determines which wavelength of light will couple back through the narrow aperture in the amplifier chip into the flared gain region. The flared gain region ensures high power amplification of forward propagating light while maintaining a single spatial mode of oscillation.

The invention also includes related master oscillator power amplifier (MOPA) devices in which a first portion of the above described semiconductor active medium is located within the resonant cavity to form a laser oscillator with external rear reflector, while a second portion of the same active medium is located outside the resonant cavity to form an optical power amplifier that is optically coupled to the laser oscillator.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic top plan view of a wavelength tunable, external cavity, semiconductor laser of the present invention.

FIG. **2** is a schematic side view of another wavelength tunable, external cavity, semiconductor laser of the present invention.

FIGS. **3A** and **3B** are respective top and side plan views of the wavelength tunable, external cavity, semiconductor MOPA device of the present invention.

FIG. **4** is a schematic top plan view of a broadband tunable, external cavity, semiconductor MOPA device of the present invention.

FIG. **5** is a schematic top plan view or yet another external cavity semiconductor laser embodiment of the present invention.

FIGS. **6A–6H** are top plan views of eight possible light amplifying diode heterostructures or "amplifier chips" for use in the laser and MOPA embodiments of FIGS. **1–5**.

FIG. **7** is a top plan view of yet another amplifier chip for use in the laser and MOPA embodiments of FIGS. **1–5**.

FIG. **8** is a side sectional view taken along the line **8—8** in FIG. **7**.

FIG. **9** is a top plan view of still another amplifier chip for use in the laser and MOPA embodiments of FIGS. **1–5**.

FIG. **10** is a side view of an alternate external cavity semiconductor laser of the present invention with vertical output.

FIG. **11** is a top plan view of another external cavity semiconductor laser embodiment of the present invention.

FIG. **12** is a side view of yet another external cavity semiconductor laser of the present invention.

FIG. **13** is a perspective view of an alternative amplifier chip for use in lasers of the present invention.

FIG. **14** is a side schematic view of an external cavity laser using the amplifier chip of FIG. **13**.

FIG. **15** is a perspective view of a monolithic array amplifier chip of the present invention.

FIG. **16** is a top plan view of a laser array using the amplifier chip of FIG. **15**.

FIG. **17** is a top plan view of a frequency switchable laser embodiment of the present invention.

FIGS. **18–24A** and **24B** are top plan views of alternate external cavity lasers of the present invention.

FIGS. **25A** and **25B** are respective top and side plan views of a wavelength tunable, external cavity, semiconductor laser of the present invention with differential pumping.

FIG. **26** is a schematic top plan view of an external cavity MOPA embodiment of the present invention with a tunable grating integrated on the amplifier chip of the MOPA device.

FIGS. **27–32** are top plan views of additional semiconductor lasers of the present invention with an integral spatial mode after and integral cavity reflectors.

BEST MODE FOR CARRYING OUT THE INVENTION

With reference to FIG. **1**, an external-cavity semiconductor laser, in accord with one embodiment of the present invention, has an active gain medium that is a light amplifying diode heterostructure or "amplifier chip" **11**, and also has a light reflective, external, diffraction grating **15** and a lens **13**. The amplifier chip **11** shown in FIG. **1** has a single mode waveguide section **17** incorporated on the grating side of the chip, opening into a flared gain section **19** on the output side of the chip. Preferably, the flared gain region **19** is linearly flared and increases in width toward the front output facet **21** of the amplifier chip **11** at a rate that is slightly greater than the divergence of light propagating within the flared gain region **19**. The front output facet **21** is typically coated for low reflection. Though a facet reflectivity of 30% would likely be acceptable, typically the reflectivity of the coated facet **21** is less than 10%, with a 2 to 3% reflectivity being preferred. The rear facet **23** on the grating side of the amplifier chip **11** is antireflection coated in order to suppress self-oscillation of the chip. A reflectivity of 1% or less is preferred

The lens **13** is a high numerical aperture lens positioned to receive and collimate light emitted from the single-mode waveguide **17** through the antireflection-coated rear facet **23**. A spherical lens with a focal length of about 6.5 mm is typical. A graded-index (GRIN) rod lens could also be used. Although a simple single element lens is shown, a more complex lens system to correct for astigmatic and chromatic aberration or other optical phenomena could be used.

The front output facet **21** of the amplifier chip **11** and the external grating **15** form a frequency-selective optical resonator in which diffraction from the reflective grating **15** provides frequency-selective feedback of light into the single mode waveguide section **17** of the amplifier chip **11**. The wavelength can be tuned by rotating the grating **15** about a pivot point **25** until an orientation is reached that couples light of the desired wavelength back through the lens **13** and into the single mode waveguide section **17**. For first order diffraction, the wavelength λ is given by the equation $\lambda=2\Lambda \sin \Theta$, where Λ is the grating pitch or tooth spacing and Θ is the angle of light incidence and diffraction with respect to the grating normal, as shown in FIG. **1**. A typical diffraction grating for use in the present invention has a line density of about 1200 mm^{-1} (Λ=833 nm) and has a first-order-diffraction differential efficiency η_{-1} which is greater than 70%. Small rotations of the grating **15** can be done with a piezoelectric transducer **27** or by a mechanical rotor.

Preferably, the axis of rotation of the grating **15**, defined by the pivot point **25**, will be positioned so that the cavity length is adjusted to compensate for the change in wavelength as tuning takes place, in order to minimize mode hopping. This compensation will occur when $R=L \cos \Theta_0/\tan \Theta_0$, where R is the distance along the grating **15** from the pivot point **25** to the optic axis of the cavity, as shown in FIG **1**, Θ_0 is the angle of light incidence and diffraction with respect to the grating normal for a grating orientation corresponding to a wavelength **[**length**]** λ_0 near the center of the desired wavelength range, and L is the total optical length of the cavity at that grating orientation. Then, for small changes in orientation ($\Delta\Theta$), the wavelength will tune ($\Delta\lambda$) at the same rate as the longitudinal modes of the external cavity ($\Delta L=m\Delta\lambda$, where m is a positive integer). This results in longer continuous tuning ranges, as previously demonstrated by Schremer and Tang in IEEE Photonics Technology Letters, vol. 2, no. 1, January 1990, pp. 3–5.

In operation, the single mode waveguide section **17** incorporated in the grating side of the amplifier chip **11** acts as a spatial mode filter to enhance single spatial mode oscillation in the laser cavity. Also, in combination with the external grating reflector **15**, the narrow aperture of the waveguide section **17** acts to select an extremely narrow frequency band, effectively a single wavelength, for feedback and laser oscillation, since for any given grating orientation, only light of a particular frequency or wavelength will be diffracted back to the precise position on the amplifier chip's rear facet **23** needed to couple into the narrow waveguide section **17** of the amplifier chip **11**. Upon exiting the waveguide section **17** into the flared gain section **19**, the forward traveling waves of the light beam are allowed to freely **[**diffract**]** *diverge* as they propagate in the junction plane of the amplifier chip **11**, since the flare of the gain section **19** exceeds the divergence of the bean. The light has a diverging phase front in the gain section **19**, owing at least in part to the narrow waveguide **17** (Waveguide **17** may be as narrow as 0.5 μm to several micrometers wide to cause significant beam diffraction.), and continues to diverge after reflection from the low reflectivity output facet **21**, as seen in the amplifier chip **11** shown in FIG. **6**A. Only the central ray **31** returns through the narrow waveguide section **17**. Since the low intensity portion of the light beam diverges in traveling back to the narrow end **29** of the gain section, the narrow end **29** and waveguide **17** act as a spatial filter or aperture to enforce single mode oscillation. Higher order spatial modes experience significantly greater diffraction losses within the optical cavity (in addition to having poorer overlap with the flared gain element **19**) and are therefore suppressed to high threshold current levels. The external cavity with flared gain section effectively acts as a resonator with a highly selective spatial filter, which minimizes the net loss of the lowest order mode relative to higher order modes. It is desirable that optical power be output through the low reflectivity facet **21**. Alternatively, power output could be obtained by a different order of diffraction off of the grating **15** or by placing a partial beamsplitter in the external cavity.

In FIG. **1**, the external rear grating reflector **15** is oriented so that the lines or grooves of the grating, as well as the rotation axis about pivot point **25**, are perpendicular to the plane of the pn junction in the diode heterostructure **11**. However, such an orientation is not essential. FIG. **2** shows an alternate embodiment in which an external rear grating reflector **34** is oriented so that the lines or grooves of the grating reflector **34** and the rotation axis about the pivot point **20** are parallel to the plane of the pn junction **26** of the diode heterostructure or "amplifier chip" **22**. A resonant optical cavity is defined by the grating reflector **34** and a lower reflectivity front facet **28** of the amplifier chip **22**. The orientation of the grating reflector **34** selects the narrow wavelength band of light that will resonate in the cavity, since only light of the selected wavelength will be reflected back upon the incident light path and be imaged by the lens **32** onto the AR coated intracavity rear facet **30** of the amplifier chip **22** at a position that will allow it to be recoupled back into the transverse waveguide **24** within the amplifier chip **22** Other wavelengths of light will be diffracted at different angles and so will be imaged by lens **32** either above or below the position of the waveguide **24**. The grating orientation shown in FIG. **2** is the more conventional orientation. All figures showing an external grating as a portion of the cavity can be used with the grating orientation of FIGS. **1** or **2**.

In FIGS. **1** and **2**, the resonant cavity is defined between the external rear grating reflector **15** or **34** and a front facet reflector **21** or **28** of the amplifier chip **11** or **22**. Thus, the entire active light amplifying region **17** and **19** or **26** is located within the resonant cavity and the resulting device is a semiconductor laser oscillator providing a coherent light output. Alternatively, referring to FIGS. **3**A and **3**B, the resonant cavity can be defined between an external rear grating reflector **44** and a distributed Bragg reflector (DBR) grating **38** or a microcleaved or ion milled reflector integrated within the amplifier chip **36**. A first, single mode waveguide, portion **40** of the active gain medium is located within the resonant cavity, while a second, flared amplifier, portion **50** of the active gain medium is located outside the resonant cavity. The single mode waveguide section **40**, DBR grating **38** and flared amplifier section are monolithically integrated in amplifier chip **36** with two AR coated end facets. The resulting device is a master oscillator power amplifier (MOPA) device in which the external grating reflector **44**, a collimating and focusing lens **42**, the single mode waveguide section **40** and the DBR grating **38** (or microcleave reflector) form an external cavity laser oscillator and the flared amplifier section **50** of the amplifier chip **36** forms an optical power amplifier optically coupled to the laser oscillator. The flamed amplifier section **50** does not provide substantial feedback to the laser oscillator. This device can be wavelength tunable, if the external grating **44** can be angularly rotated and if the DBR grating **38** (or microcleave reflector) has a broadband reflectivity. In the case of use of a DBR grating **38** as a cavity reflector, a lower value of the parameter K·L, where K is the coupling coefficient of the grating to the lightwaves and L is the grating length, is desirable for a wider tuning range. Alternatively, grating **38** may be electrically timed in wavelength to match the tuning of external reflector **44**, or the reflector **44** may be replaced with a plane minor and the grating **38** used as the only wavelength tuning means.

With reference to FIG. **4**, the amplifier chip **52** may have a series of short DBR grating segments **58**$_1$, **58**$_2$, . . . , **58**$_N$ of various grating pitches Λ_1, Λ_2, . . . Λ_N between the flared amplifier section **54** and the single mode waveguide section **56** on the chip **52**. A resonant optical cavity is defined between an external rear grating reflector **64** and a selected DBR grating segment **58**$_1$, **58**$_2$. . . . , **58**$_N$ that depends on the orientation of the external grating reflector **64**. Thus, the external grating reflector, a collimating and focusing lens **62**, the single mode waveguide section **56** and the selected DBR grating segment **53**$_1$, **58**$_2$, . . . , **58**$_N$ form a laser oscillator, which is coupled to a flared optical power amplifier **54** to form a broadband tunable MOPA device. Whereas the tunability of the MOPA device shown in FIGS. **3**A and **3**B is limited to a relatively narrow range of wavelengths corresponding to the narrow reflection band of the single DBR grating **38**, the MOPA device in FIG. **4** can be tuned over a broader wavelength range corresponding to the stepwise-continuous reflection bands $\lambda_1 \pm \Delta\lambda_1$, $\lambda_2 \pm \Delta\lambda_2$, . . . , $\lambda_N \pm \Delta\lambda_N$ of the DBR grating segments **58**$_1$, **58**$_2$, . . . , **58**$_N$ and limited only by the gain band of the diode heterostructure **52**.

With reference to FIG. **5**, an external cavity diode laser has an amplifier chip **66** with a single mode waveguide section **68** coupled to a flared gain section **70**. The resonant cavity is defined between an external rear reflector **78**, here a highly reflective ($R \approx 98\%$) planar mirror surface, and a front facet **72** of the amplifier chip **66**. Rear facet **74** of the amplifier chip **66** is low reflectivity or antireflection (AR) coated. A lens **76** collimates light emitted from the single mode waveguide **68** through rear facet **74** and focuses reflected light back into the waveguide **68**. In this embodiment, an optical power monitor **80**, such as a silicon photodetector, could be placed behind mirror surface **78** to receive the small amount of light transmitted through the mirror surface **78** for monitoring the power level. The detected power level could then be used to control the pump current applied to amplifier chip **66** in order to maintain relatively stable output powers. Monitoring could also be used to verify amplitude modulation. A lens system **82** may be placed in the path of the output beam in front of front facet **72** to collimate the output beam. Because of the different lightwave beam waist positions in the lateral and vertical directions, a cylindrical lens system may be required.

In FIGS. **6**A–**6**H, eight possible amplifier chip embodiments for use in the external-cavity configuration shown in FIGS. **1**–**5** are depicted. The amplifier chip **11** seen in FIG.

6A is the same as that shown in FIG. **1** and has a single mode waveguide section **17**, at a rear end of the chip **1**, followed by a flared gain section **19** at a front, output, end of the chip **11**. The amplifier chip **11** has an antireflection coated or nearly-AR coated rear facet **23** and a low reflectivity front facet **21**. The width of the narrow end of the gain section **19** is the same as the width of the waveguide **17**. In FIG. **6**B, an amplifier chip **33** also has a single mode waveguide section **35** and a flared gain section **37**. However, the narrow end **39** of the gain section **37** has a width W which is not equal to the width of the waveguide **35**, but is instead wider than the waveguide section **35**. As in the amplifier chip **11** in FIG. **6**A, the gain region **37** of amplifier **33** is preferably linearly flared and increases at a constant rate that is slightly greater than the divergence of light propagating in the gain region **37**. However, gain sections with nonlinear flares, i.e. having increases in width that are not at a constant rate across the length of the gain section **37** or broad area gain sections, could also be used. The amplifier chip **33** has an antireflection coated rear facet **43** and a low reflectivity front output facet **41**. In FIG. **6**C, another amplifier chip **45** has only a flared gain region **47** and no single mode waveguide section. The flared gain region **47** has a narrow aperature end **49** at the antireflection coated rear facet **51** and a broader output end at low reflectivity front output facet **53**. The flared gain regions **19**, **37** and **47** in FIGS. **6**A–C increase the optical output power while maintaining a single spatial mode. Typically, 5 mW cw power at the narrow input end **29**, **39** and **49** of the gain regions are increased over a length of 100 μm or more to greater than 1 W cw output power at the output facets **21**, **41** and **53**. The flared amplifier configuration maxi s efficiency by expanding the gain volume along the length of the amplifier as the optical power grows, so that near uniform power density and saturated carrier density are maintained throughout the gain region.

In FIG. **6**D, an amplifier chip **55** has separate conductive contacts **57** and **59** for the single mode waveguide **61** and flared gain section **63**. Each section **61** and **63** can thus be pumped independently with separate electrical currents I_1 and I_2. One use of such a configuration is for intensity modulation of the laser. As a result of the individual contacts **57** and **59**, the output power emitted through low reflectivity output facet **65** can be modulated by simply modulating the pump current I_1 supplied to the single mode waveguide section **61**, instead of trying to modulate a single larger pump current provided to the entire amplifier chip. Higher speed modulation and lower modulation current requirements are thus achieved with this amplifier chip configuration. The independently pumped single mode waveguide section **61** might also be used as a preamplifier to bring the optical power coupled into it from the feedback grating **15** up to saturation levels before the light enters the flared gain section **63**. Also, the single mode waveguide section **61** could be used as a phase-control section in which the amount of current I_1 injected into the phase control waveguide section **61** is adjusted to vary the refractive index in the waveguide and thereby effectively control the total optical length of the cavity to minimize mode hopping and extend the tuning range. Such a technique is described by M. Notomi et al. in IEEE Photonics Technology Letters, vol. 2, no. 2, pages 85–87 (1990). More than two separate contacts might also be present on the amplifier chip. For example, the flared gain section **63** could be differentially pumped with a lower current density provided by one conductive contact to the input end **67** of the flared gain section **63** and a higher current density provided by another conductive contact closer to the output end of the gain section **63** near facet **65**.

Such differential pumping will reduce noise in the optical output signal. Differential pumping with a lower current density in region **67** versus other portions of the flared gain section **63** will also increase the diffraction-limited output power significantly over that obtained from a uniformly pumped flared region **63**.

Referring to FIG. **6**E, differential pumping of an amplifier chip **92** may also be achieved by means of a selective proton implantation in the gain regions **84** and **86** during fabrication of the chip **92**. The varying densities of implanted proton sites in the surface of the amplifier chip **92** cause varying resistivities to electric current over the length of the gain regions **84** and **86**. As a result, a uniform bias voltage applied to the gain regions **84** and **86** will produce a current density distribution that varies in different areas of those gain regions **84** and **86**, producing differential pumping. In the particular embodiment shown in FIG. **6**E, the density of [stipling] *stippling* in the drawing represents the surface conductivity in a particular area of the illustrated amplifier chip **92**. Thus it can be seen that the rear portion of the flared gain section **86** nearest the narrow aperture **90** connecting the flared gain section **86** to the waveguide section **84** has a lower surface conductivity, and thus is pumped with a lower current density, than the broad front portion of the flared gain region **86** nearest the low reflectivity front output facet **88** of the amplifier chip **92**. The single-mode waveguide section **84** could have a conductivity which is like the front portion of the flared gain region **86** or intermediate or equal or higher in value between the high and low conductivity front and rear portions of the flared gain section **86**. Regions near facets **88** and **89** may be left unpumped to ensure long life at high power, such as in a window laser formed by quantum size effects, impurity induced disordering, doping, composition change or other means.

With reference to FIG. **32**, differential pumping can also be done using an unpumped transparent region **392** as one of the segments of the differentially pumped flared region **391**. This represents the extreme cast in which the pump current density is zero in a first portion **392** of the flared region **391**. The unpumped transparent region **392** allows the beam to diverge without forming filaments. Transparency can be achieved for zero current density by means of quantum size effects, impurity induced disordering, doping, composition change or other means. The transparent region **392** should be proximate to the single mode light aperture region **393**. The end facets **396** and **397** can be AR coated or low reflectivity coated for a flared optical power amplifier, or HR coated and low reflectivity coated (about 5% reflectivity) for a flared laser oscillator. Further, if an internal reflector, such as a DBR grating, is formed, the device with transparent unpumped region **392** in the flared region **391** could form a MOPA device.

With reference to FIG. **6**F, the amplifier chip **100** is essentially that used in the MOPA device of FIGS. **3**A and **3**B. The amplifier chip **100** includes a single mode waveguide section **102** terminating in a DBR grating **104** and followed by a flared amplifier section **106**. End facets **108** and **110** of the chip **100** are antireflection coated.

In FIG. **6**G, the amplifier chip **100**a also includes a single mode waveguide section **102**a followed by a flared section **106**a, and AR coated or low reflectivity facets **108**a and **110**a. However, here the DBR grating **104**a is located in the flared section **106**a. In a configuration like that shown in FIGS. **3**A and **3**B, the laser oscillator will include the portion of the flared section **106**a that is located between the single mode waveguide section **102**a and the DBR grating **104**a, while the optical power amplifier comprises the remaining portion of flared section **106**a between the DBR grating **104**a and end facet **110**a. The internal reflector **104**a could also be an etched mirror.

With reference to FIG. **6**H, the amplifier chip **122** has a single mode waveguide **124** that tapers in a section **126** to a smaller aperture leading into the flared amplifier section **128** to increase the beam divergence in the flared region **128**. As in previous embodiments, end facets **130** and **132** are coated for low reflectivity.

All of the amplifier chips **11**, **33**, **45**, **55**, **92**, **100**, **100**a and **122** in FIGS. **6**A–**6**H are light amplifying diode heterostructures with their front and rear facets suitably coated to prevent self-oscillation. Only when at least one external reflector, such as the grating **15** in FIG. **1**, is provided to help establish a resonant optical cavity will laser oscillation occur. Alternatively, if the rear facets of each of these devices is HR coated devices **11**, **33**, **45**, **55**, **88**, **92**, **100**a, and **122** can form unstable resonator lasers which are stable to high coherent power levels and do not rely on an external reflector. Tunable gratings replacing either reflector can result in broadband wavelength tuning of such a monolithic device. Various heterostructure material compositions, such as GaAs/AlGaAs, InGaAs/AlGaAs, InP/InGaAsP and the like, could be used. Likewise, various known strained, graded index and lattice matched structures, as well as various known current, carrier and optical confinement structures, including single and multiple quantum well structures, may be used. In the case of frequency tunable lasers, such as the grating tuned laser in FIG. **1**, it is desirable to tailor the gain of the amplifier chip so that it remains somewhat constant over a wide wavelength range. Such a light amplifying diode heterostructure exhibiting a broadband gain-flattened spectrum can be achieved in single quantum well structures at high pump current densities, as described by M. Mittelstein, et al. in Applied Physics Letters, 54(12), pp. 1092–1094 (1989). The amplifier chip's active region can be optimized for use in external cavities like that shown in FIG. **1** by reducing the optical confinement Γ in the transverse direction perpendicular to the pn junction of the chip in order to reduce the transverse or vertical divergence of light emitted from front and rear facets. In this way, the coupling efficiency of external optical elements is increased. A further advantage of a lower optical confinement Γ is that leasing associated with charge variations and gain saturation is reduced.

With reference to FIGS. **7** and **8**, the amplifier chip **71** may have a detuned grating output coupler **73** integrated therein for providing surface emission **75** of the laser output, rather than end emission from a front facet **77**. The detuned grating is located adjacent to the front facet **77** at an end of the flared gain section **79** of the amplifier chip **71** so that the amplified light propagating in the waveguide defined by the active region **81** and cladding layers **83** is coupled by the grating **73** vertically out of the waveguide and through a top (or bottom) surface **85** of the amplifier chip **71**. The narrow aperture end **87** of the flared gain section **79** at the rear end thereof is optically coupled to an antireflection (AR) coated near facet **91**, preferably, but not necessarily, via a single mode waveguide section **89**. The overall effective reflectivity of the grating **73**, front facet **77** and output surface **85**, taken together, is generally low, i.e. less than about 30%, and typically less than about 10%. One result of the grating coupled surface emission **75** from the amplifier chip **71**, when used in a frequency selective external cavity like that shown in FIG. **1**, is that the output beam direction is longitudinally steered, forward or backward, as the frequency is tuned, due to the wavelength dependent nature of the diffraction angle of the grating output coupler **73**. Alternatively, front facet **77** may be AR coated and grating **73** may be a tuned grating to provide feedback. In this case, the planar mirror external cavity configuration of FIG. **5** is probably preferable and grating **73** may be wavelength tunable.

With reference to FIG. **9**, an amplifier chip **120** with a single mode waveguide section **112** and a flared gain section **114** located between a pair of parallel planar end facets **116** and **118**, of which facet **116** is antireflection coated, has a curved grating output coupled **119** at the broad end of the flared gain section **114**, instead of the straight grating **73** of FIGS. **7** and **8**. Light emerging from the waveguide **112** at the narrow aperture **117** freely **[**diffracts**]** *diverges* in the flared gain section **114** as a divergent beam. The divergent beam is characterized by curved phase fronts. The grating output coupler **119** is a detuned surface emitting grating, like the grating **73** in FIGS. **7** and **8**, but has a curvature that matches the curved phase fronts of the lightwaves propagating in the flared gain section **114**. The light emerges through a top or bottom surface of the amplifier chip **120** as a substantially collimated beam. Single spatial mode filtering by the aperture **117** of the reflected light returning to the waveguide **112** works best if the back reflectivity of the curved grating **119** is minimized and made substantially less than the low reflectivity of the planar front facet **118**.

Alternatively, an angled external front grating reflector **97**, receiving light emitted through a front end facet **94** of an amplifier chip **93** with a flared gain region, may be used instead of the integral detuned grating **73** in FIGS. **7**–**9** to redirect the light into a vertical or transverse direction, as shown in FIG. **10**. If the amplifier chip **93** is positioned within a frequency selective external cavity having a lens **13** and an external rear grating reflector **15**, as shown in FIG. **10**, then the external front grating reflector, outside of the laser cavity defined by the grating **15** and facet **94**, will also steer the direction of the reflected beam **99** longitudinally, that is, forward and backward, as the wavelength of the emitted light is tuned by the orientation of rear grating **15**. A collimating lens or lens system **95** may be placed between the front facet **94** of the amplifier chip **93** and the external front grating reflector **97**, so that the emitted light received by the front grating **97** has the same angle of incidence upon the grating **97**, regardless of the position of incidence of individual light rays. Alternatively, the grating reflector **97** could be curved to receive the diverging light directly from the emitting facet **94** and reflect it in a collimated beam **99**. If longitudinal steering of the beam **99** as the wavelength λ is tuned is not needed or desired, an angled planar or concave minor could be used in place of the front grating reflector **97** to simply redirect (or both it and collimate) the light output.

With reference to FIG **11**, an amplifier chip **101** is positioned in an external cavity having a lens **103** and an external rear grating reflector **105**. The amplifier chip **101** itself has a single mode waveguide section **107** followed by a flared gain section **109**. The front facet **111** of the amplifier chip **101** has low reflectivity, establishing a resonant cavity with the rear grating reflector **105**. In this embodiment, the back facet **113** of the amplifier chip **101** is formed with a Brewster angle surface **115** at least at the aperture of the single mode waveguide section **107**. The Brewster angle surface **115** can be formed by ion beam milling and may be oriented, as shown, with the normal or perpendicular to the surface **115** parallel to the pn junction of the amplifier chip **101**. Alternatively, the normal to surface **115** could be perpendicular to the pn junction. The orientation in which the Brewster angle surface **115** is formed determines whether the TE or TM polarization mode of oscillation is supported by the cavity. The Brewster surface **115** also increases the continuous tuning capabilities of the external cavity by directing any light reflected by the surface **115** out of the single mode waveguide **107**, thereby effectively minimizing back facet reflectivity and preventing self-oscillation of the amplifier chip **101**. The facet **113** and Brewster surface **115** might additionally be antireflection coated.

With reference to FIG. **12**, another amplifier chip **121**, located in an external cavity with a lens **123** and external grating reflector **125**, has a single mode waveguide section **127** and a flared gain section **129** as in any of FIGS. **6A–6H** and **7**. A front end output facet **131** is of low reflectivity and defines a resonant cavity along with the external grating reflector **125**. The orientation of the grating **125** can be adjusted to select the frequency of laser oscillation. The amplifier chip **121** also has a back facet **133** that is tilted at an angle, typically about 45°, sufficient to cause it to be totally internally reflecting of backward propagating light in the waveguide and also of light fed back by grating reflector **125** and focused by lens **123** onto the facet **133** in the neighborhood of the single mode waveguide section **127**. Light is thus coupled vertically through a substantially nonreflective top (or bottom) amplifier chip surface **135**. Surface **135** can be AR coated also. Use of the totally internally reflecting angled back facet **133** minimizes self-oscillation, because backward propagating light from the waveguide section **127** is reflected vertically out of the waveguide and allowed to freely **[**diffract**]** *diverge* in the amplifier chip **121** before reaching the output surface **135**. Any light reflected by the substantially nonreflective output surface **135** has little chance of being coupled back into the waveguide section **127**.

With reference to FIGS. **13** and **14**, in order to reduce the alignment sensitivity of the external cavity laser, the back facet **143** of the amplifier chip **141** can be coated such that a top portion of the facet **143**, including the light emitting aperture **145**, is antireflective, while a bottom portion of the facet **143** is highly reflective. The amplifier chip **141** is otherwise like any of those shown in FIGS. **6A–H**, with an optional single mode waveguide section **147** and with a flared gain section **149** in which light propagates in a waveguide **151** and is amplified. The front light emitting end facet **153** has low reflectivity and forms, along with an external rear reflector **157**, an external resonant cavity. Rear reflector **157** can be a planar mirror or a grating reflector. A lens **155** is positioned between the rear facet **143** of the amplifier chip **141** and the external rear reflector **157** to collimate the light emitted from the narrow waveguide section **147** through the aperture **145** and to bend the light path slightly downward. This light is reflected by the rear reflector **157** back toward the lens **155**, which then focuses the light onto the HR coated bottom portion of rear facet **143**. The light is then reflected from the HR coating back toward the lens **155**, where it is collimated and bent onto a slightly upward return path. Being reflected a second time from the external rear reflector **157**, the light is finally focussed by the lens **155** back onto the aperture **145** and coupled into the waveguide **147**. In this way, difficult alignment tolerances in the direction perpendicular to the pn junction are reduced, because the vertical alignment of the amplifier chip **141** with the lens **155** and external rear reflector **157** only determines the amount of light path bending by the lens **155**, and does not adversely affect the coupling of light back through the aperture **145**. In place of the lens **155** and planar rear reflector **157**, a suitably curved external rear reflector could be used, as described in U.S. Pat. No. 4,797,894 to Yaeli. In the case where the external rear reflector **157** is a frequency selective grating reflector, as seen in FIG. **1**, the reflection of light twice off of the rear reflector **157** provides an additional advantage. Due to two pass operation of the grating reflector **157**, the spectral line width of the light coupled back into the aperture **145** is reduced substantially.

With reference to FIGS. **15** and **16**, an amplifier chip **161** may have a monolithic array of sources **162**, **163**, etc. for simultaneous operation in multiple wavelengths λ_1, λ_2, etc. Each source **162**, **163**, etc. on the amplifier chip **161** is constructed, as in FIGS. **6A–H** and **7**, with a flared gain section **164** and a spatial mode filter, such as a single mode waveguide section **165**, at the narrow end of the flared gain section **164**. The front output facet **167** at the broad end of the flared gain section **164** is characterized by low reflectivity and forms, together with an external rear grating reflector **173**, a resonant cavity for laser operation. The rear end facet **169** is antireflection (AR) coated to prevent self-oscillation of the amplifier chip **161**. The flared gain regions **164** of each source **162**, **163**, etc. in the array can be fabricated to amplify at different emission wavelengths. This is done, for example, by using a single quantum well strained layer InGaAs/InAlGaAs laser, where the gain band may be 50 nm wide. In order to make the single monolithic amplifier chip **161** capable of operating over a large wavelength range (e.g. 630 nm to 1100 nm) with each array element **162**, **163**, etc. operating over about a 50 nm bandwidth, the multiwavelength amplifier array can be fabricated as described for laser arrays in U.S. Pat. Nos. 4,925,811, 4,955,030 and 5,039,627 to Menigaux et al. These laser array structures have stacks of alternate confinement layers and active layers, with each active layer being of a different composition from the others and being characterized by a different gain wavelength. PN junctions are formed in the vicinity of different active layers in the stack by means of localized in introduction and diffusion of a p-type impurity to different depths. An alternative way to form a multiwavelength amplifier array is to use multiple amplifier chips, each having a different amplifying wavelength. In either case, light beams emitted through the apertures **170** of the multiple sources **162**, **163**, etc. at the AR coated rear facet **169** are collimated by a lens **171** and reflected from the external grating reflector **173** back through the lens **171** to be focussed on the rear facet **169**. The relative positions of the apertures **170** with respect to the lens **171** determine the amount of bending of the light paths for the various emitted beams, and therefore determine the different incidence angles of each beam on the grating **173**. Only light of particular wavelengths λ_1, λ_2, etc. corresponding to the respective incidence angles are coupled back through the apertures **170** into the amplifier chip **161**. Thus, each source **162**, **163**, etc. located in the external cavity will only oscillate at a particular wavelength λ_1, λ_2, etc. responding to the incidence angle of light from that source onto the grating **173**. The gain band of the active medium for each source **162**, **163**, etc. should be selected to match its resonance band in the cavity. A Fabry-Perot external mirror could be used in place of grating reflector **173**.

With reference to FIG. **17**, several single mode waveguide regions **175** and **177** may be coupled to a single flared gain region **179** on an amplifier chip **181** for providing a wavelength switching capability. As in FIG. **16**, the amplifier chip **181** has a front light emitting facet **183** that is of low reflectivity and that forms, along with external rear grating reflector **189**, a resonant cavity for laser oscillation. Rear facet **185** of the amplifier chip **181** is antireflection coated. A lens **187** is positioned between the rear facet **185** and the grating reflector **189**. As in FIG. **16**, the difference in position of the light emitting waveguide apertures **175** and **177** at rear facet **185** relative to the lens **187** results in a difference in incidence angle of the light beams upon the grating **189** and thus a difference in the wavelength λ_1 or λ_2 that can oscillate. The waveguides **175** and **177** should be spaced sufficiently far apart to minimize crosstalk, but sufficiently close that both wavelengths λ_1 and λ_2 fall within the gain spectrum of the common flared gain region **179**. Separate electrical contacts **191** and **193** independently bias the waveguides **175** and **177** and independently inject current I_1 and I_2 into the respective waveguides. At least one other conductive contact **195** provides current I_3 to the flared gain region **179**. Biasing only one of the waveguides **175** and **177** so as to minimize loss in the selected waveguide will select the wavelength λ_1 or λ_2 of the output beam. Alternatively, operating both waveguides **175** and **177** would lead to simultaneous multiple wavelength operation, as well as the generation of harmonics of the wavelengths λ_1 and λ_2.

With reference to FIGS. **18–28**, other cavity configurations using one of the above described amplifier chips with flared gain region are possible. For example, a saturable absorber **205** can be incorporated into the external cavity to act as a Q-switch for generating short pulses, as seen in FIG. **18**. An amplifier chip **201** having a flared gain region **202** is placed within a resonant cavity defined by a low reflectivity front end facet **209** of the amplifier chip **201** and an external rear reflector **207**. Rear reflector **207** may be a mirror surface or a grating reflector. A lens **203** and the saturable absorber **205** are positioned between an AR coated rear facet **204** of the amplifier chip **201** and the rear reflector **207**. Lens **203** receives light emitted from the narrow aperture end of the flared gain region **202** through AR coated rear facet **204** and collimates the light beam for passage through saturable absorber **205** to the rear reflector **207**. Lens **203** also receives the return light reflected from the rear reflector **207** back through saturable absorber **205** and focuses the light onto the rear facet **204** for coupling through the narrow aperture into the flared gain region **202** of the amplifier chip **201**. The cavity configuration provides for mode locked, high average and peak power operation of laser in a pulsed mode. A saturable absorber formed by an unpumped or reverse biased region in the chip along the length of the cavity can also provide mode locked operation. Synchronous pumping of at least a portion of flared gain region **202** or single mode gain region **206** at a period coinciding with the round trip transit time of light pulses in the cavity also results in picosecond pulse lengths and very high peak power outputs. The effectively unstable resonant cavity provided in part by the flared gain region **202** together with narrow, single mode, aperture **206** ensures stable, single mode operation even at high power.

As seen in FIGS. **19** and **20**, the amplifier chips **211** and **221** may be optically coupled to an external optical fiber **213** and **225**. The optical fibers **213** and **225** are preferably single mode fibers. In FIG. **19**, the fiber **213** is butted to the AR coated rear facet **214** of the amplifier chip **211** aligned with the position of the narrow single mode aperture of the flared gain region **212** of the amplifier chip **211**. In FIG. **20**, the fiber **225** is coupled via a lens **223** to receive the light emitted from amplifier chip **221** through the AR coated facet **224**. Lens **223** may be a graded-index (GRIN) rod lens, as shown. In FIG. **19**, feedback is provided by a highly reflective coating **215** on the far end of the optical fiber **213** so that a resonant cavity for laser oscillation is established between the reflective coating **215** and the low reflectivity front end facet **217** of the amplifier chip **211**. In FIG. **20**, frequency selective feedback is provided by a tunable Bragg grating reflector **227** associated with the optical fiber **225**. The fiber **225** might be held in a groove **228** formed in a support **226** and the grating reflector **227** placed over the fiber **225** on the support **226**. The end of the fiber **225** beyond the grating reflector **227** can be cleaved at an angle to minimize feedback from end reflections. The grating reflector **227** has a refractive index which is higher than the fiber's cladding so that coupling of light is via the evanescent wave leaking out of the cladding into the grating reflector **227** above. The fiber cladding may need to be thinned in this region for adequate coupling to occur. If the grating teeth are arranged in a fan shape, as shown, tuning can take place by sliding the reflector **227** from side-to-side to adjust the grating pitch in the vicinity of the fiber **225**. W. Sorin, et al. reported in Optics Letters, vol. 13, no. 9, pages 731–733 (1988) that a laser diode coupled to such an external fiber cavity is stepwise tunable over about a 66 nm range. In combination with our amplifier chip **221** with flared gain region **222**, the fiber coupled laser achieves stable, high power single frequency operation with a narrow line-width. A grating could also be formed within the optical fiber itself and be tunable by applying stress to the fiber in the grating region.

In FIG. **21**, an atomic resonance filter **235** is incorporated into the external cavity. The arrangement is similar to that shown in FIG. **18**, but with the atomic resonance filter **235** replacing the saturable absorber **205**. The cavity is defined by an external rear reflector **237**, such as a mirror or grating, and a low reflectivity front end facet **239** of an amplifier chip **231**. The amplifier chip **231** may be any of those shown in FIGS. **6A–6H, 7, 9, 11, 12, 13, 15, 16, 17, 24, 25, 26, 28** and **37** described herein. A lens **233** between the amplifier chip **231** and the atomic resonance filter **235** collimates light received from the amplifier chip **231** and focuses return light reflected from the rear reflector **237** so as to couple the light back into the amplifier chip **231**. The resulting laser produces a stable, single frequency output **240** having a frequency that is referenced to an atomic resonance frequency specified by the filter **235**.

In FIG. **22**, the external resonant cavity, defined by an external rear reflector **247** and a low reflectivity front end facet **249** of an amplifier chip **241** with flared gain region **242**, includes a birefringence filter **245** for wavelength selection. Such a birefringence filter **245** could be tunable. For example, as described by A. Schremer, et al. in Applied Physics Letters 55(1), pages 19–21 (1989), an electro-optic birefringent modulator can be placed in external cavities for wavelength tuning. Frequency modulation of the laser output could also be performed using such a configuration. The amplifier chip **241** with flared gain region **242** of the present invention ensures high power, single spatial mode outputs as the frequency is tuned or modulated.

In FIG. **23**, instead of the rear grating reflector **15** of FIG. **1**, a prism **255** and a mirror **257** could be used to provide wavelength selective feedback in the external cavity and to obtain a frequency tunable output. An amplifier chip **251** has a flared gain region **252**, as in FIGS. 2A–2D. A rear end facet **254** is antireflection coated to prevent self-oscillation, while a front end facet **259** has low reflectivity. Together, the external mirror **257** and front end facet **259** define a resonant optical cavity for laser oscillation. A lens **253** receives and collimates light emitted from the narrow aperture end of the flared gain region **252** at the AR coated facet **254**. A prism **255** is positioned between the lens **253** and mirror **257** and oriented for refracting the collimated beam received from lens **253**. Preferably, prism **255** is made of a material, such as dense flint glass, that has high dispersion $|d\lambda/d\Theta|$ in the wavelength band coinciding with the gain band of the amplifier chip **251**. The orientation of the mirror **257** determines which wavelength of light will be incident perpendicular thereon and therefore which wavelength will be fed back into the gain region **252**.

With reference to FIG. **24**, the single mode waveguide **263** serving as a spatial mode filter in amplifier chip **260** need not extend all of the way to the antireflection (AR) coated intracavity rear facet **267**. Rather, a short flared region **265** could be provided in the amplifier chip **260** between the single mode waveguide **263** and the rear facet **267**. As in previous laser embodiments, the resonant cavity is defined between an external rear grating reflector **274** and a low reflectivity front facet **269** of the amplifier chip **269**. In operation, light that has the particular wavelength to be reflected by the grating reflector **274** back onto its incident light path will be focussed by lens or lens system **272** through the rear facet **267** into the short flared region **265**. The short flared region **265** tapers down to the single mode waveguide **263** at a rate that allows the light to be efficiently coupled into the waveguide **263**. Forward propagating light emerging from the single mode waveguide **263** is then allowed to freely diffract and diverge in the principal flared gain **261** of the amplifier chip **260**, in which the optical power is increased to high levels at the output facet **269**.

With reference to FIGS. **25**A and **25**B, a light amplifying diode heterostructure **280** with a pn rectifying junction **282** for providing an active region for amplification of lightwaves has a single mode waveguide section **284** for guiding propagation of the lightwaves and a two-part flared gain section **286**a and **286**b in which the lightwaves are allowed to freely **[**diffract**]** *diverge* as they are amplified. In this embodiment, proton surface implants **288** electrically isolate the respective waveguide section **284** and flared gain section parts **286**a and **286**b so that each isolated part can be separately pumped with a different amount of electric current I_1, I_2 and I_3. Other electrical isolation techniques, such as selective surface etching, could be used in place of proton surface implants **288** to provide the isolation. Separate conductive surface contacts for each region apply the different current levels I_1, I_2 and I_3 to the respective regions. Current I_1 applied to single mode waveguide **284** may be adjusted to optimally excite the narrow aperture end of flared gain region **286**a and/or can be modulated to modulate the laser output. Current I_2 applied to the narrower rear part **286**a of the flared gain region may be lower than the current I_3 applied to the broader part **286**b in order to minimize amplification of signal noise and to suppress the formation of filaments. Current I_2 could also be modulated to modulate the laser output. The laser's resonant cavity is again defined by an external rear grating reflector **294** for frequency tunability and by a low reflectivity front output facet **292** of the amplifier chip **280**. Alternatively, the grating reflector **294** may be replaced by a plane mirror. In this case, multiple longitudinal mode operation is possible and mode locking of the output can be achieved by modulation of at least a portion of the single mode waveguide **284** (or other regions) with a current at a frequency of c/2nL, where c/n is the speed of light in the cavity and L is the cavity length. Also, note that passive mode locking could also be used. A reverse bias section of waveguide **284** could provide a saturable absorbing region, for example. Further, note that mode locking is possible, if external reflector **294** were replaced by a reflective surface for facet **290**, thus making the device entirely monolithic. A lens or lens system **296** collimates light emitted from the single mode waveguide **284** tough antireflection coated rear facet **290** for reflection by the grating **294** and focuses the light reflected by the grating **294** back onto rear facet **290** for coupling into waveguide **284**.

With reference to FIG. **26**, a MOPA device **301** includes an amplifier chip **303** with antireflection (AR) coated end facets, an external rear reflector **305** and a collimating and focusing lens **307**. The amplifier chip **303** includes a single mode waveguide section **309** to which a first current I_1 is applied, distributed Bragg reflector (DBR) grating **311** at an end of the waveguide **309** to which a tuning current I_t or a tuning bias voltage V_t may be applied, and a two-part flared amplifier section **313**a and **313**b optically coupled via the grating **311** to the waveguide **309** to which respecting amplifying currents I_2 and I_3 can be applied. The resonant optical cavity of the MOPA's laser oscillator is defined by external rear reflector **305** and the wavelength tunable grating **311** integrated in the chip **303**. This embodiment, thus, can tune the wavelength of the MOPA device's light output beam by changing the tuning bias V_t or current I_t that is applied to the integral DBR grating **311**. In operation, wavelength tuning may or may not be desired. Currents I_2 and I_3 may be differentially pumped with a lower current density under I_2 to provide high coherent output power. A different series resistance in these regions could provide the same benefit. Tailoring the chip's internal resistance, as in FIG. **6**E, could allow I_1, I_2 and I_3 to all be driven from the same electrical contact. Current I_1 may also be used for phase control timing between mirror **305** and grating **311**.

Each of the above-described lasers and MOPA devices is characterized by a light amplifying diode heterostructure or amplifier chip with a flared gain region that allows light propagating therein to freely **[**diffract**]** *diverge*. In the lasers of the present invention, the diverging light which is partially reflected by the low reflectivity front end facet continues to diverge, so that only the central rays pass through the narrow aperture end of the flared gain region and through the antireflection coated rear facet of the amplifier chip to the external rear reflector of the resonant cavity. Effectively, the cavity acts as a marginally stable resonator with a single mode spatial filter that ensures a single spatial mode of oscillation. The light output from the broad front end of the flared gain region is characterized by high powers (in excess of 1 W cw) and good modal quality. Embodiments with frequency selective elements in the external cavity are tunable over a bandwidth of at least 50 nm and provide stable, single frequency and narrow linewidth outputs even at high output power levels.

With reference to FIG. **27**, a laser made up of a light amplifying semiconductor diode heterostructure **321** includes a pair of reflection cleaved end facets **323** and **325** integral with the heterostructure **321** for providing feedback of light and for defining an optical resonant cavity for laser oscillation. The heterostructure **321** has a multimode gain region **327**, preferably flared, permitting the propagation of light therein with a diverging phase front. The flared gain region **327** has a single spatial mode light aperture **329** at a narrow end of the flared gain region **327**. The aperture **329** preferably comprises a single mode waveguide section **331** in the diode heterostructure **321** optically coupled at one end to the flared gain region **327**. The opposite end of the waveguide **331** terminates in the rear end facet **323**, which is preferably coated for high reflectivity. The front end facet **325** at the broad end of the flared gain region **327** furthest from the single mode aperture **329** has a low reflectivity of at least about 0.5%, but preferably not more than about 5%. A reflectivity of about 1% is typical. The diverging light that is reflected by front end facet **325** continues to diverge. Only the centralmost rays couple through the narrow aperture **329** into the waveguide **331** to be reflected by the rear facet **323**. Lossy regions **333** may be provided at the side edges of the waveguide **331** and gain region **327** near the aperture **329** in order to suppress oscillation of any light that could be coupled out of the gain region **327** into other portions of the diode heterostructure **321** other than through the light aperture **329**. The lossy regions **333** may be low bandgap absorption regions formed by impurity induced disordering or implantation or by epitaxial growth of different levels or heights, such as by growth upon a terraced or channeled substrate. Alternatively, the top heterostructure layers could be etched away in these regions **333** down through the active layer or layers. Laser light **335** is emitted through the low reflectivity front end facet **335**, where it could be collimated by an external lens system, not shown.

Referring now to FIGS. **28** and **29**, one of the reflective cleaved end facets **323** or **325** of FIG. **27** may be replaced by a grating reflector **335** or **337** at one end of the diode heterostructure **341** or **351**. In FIG. **28**, the grating reflector **335** is located at the broad end of the flared gain region **339**. The end facet **343** adjacent to grating reflector **335** is antireflection coated to suppress Fabry-Perot cavity modes. Differential pumping of flared gain region **339** is provided by creating resistive regions R by ion implantation or other means. In FIG. **29**, the grating reflector **337** is located at the rear end of single mode waveguide section **353**. The rear end facet **355** proximate to rating reflector **337** may be oriented at a nonperpendicular angle Θ relative to the principal direction of light propagation in waveguide section **353** and flared gain region **357** in order to suppress reflection from this surface. The grating reflectors **335** and **337** provide single frequency reflection of lightwaves in the resonant cavity and can be tuned by a bias voltage V_{tun} or tuning current I_{tun} applied to a conductive contact above the gratings **335** and **337** so as to adjust the wavelength reflection response of the ratings **335** and **337**. In addition to a pump current **[**Ig**]** I_g applied to single mode waveguide sections **345** and **353**, a separate phasing current I_Φ may also be applied to an area of the waveguide sections **345** and **353** to adjust the optical path length of the resonant cavity to match the phase of the light propagating in the cavity to the selected wavelength. This enables continuous wavelength tuning by adjusting the tuning voltage or current V_{tun} or I_{tun} and the phasing current I_Φ in concert to prevent or minimize longitudinal mode hopping as tuning takes place. The flared gain regions **339** and **359** can be differentially pumped along their lengths either by applying a single amplification current I_{amp} and providing surface resistive regions R in the narrower area of the gain region **339**, as in FIG. 28, or by applying separate amplification currents I_{amp1} and I_{amp2} to respective narrower and broader areas of the flared gain region **357**, as seen in FIG. 29.

With reference to FIG. **30**, a flared laser oscillator **361** includes two single spatial mode waveguide sections **363** and **365** connected to a narrow end of a common flared gain region **367**. The resonant cavity is defined between reflective cleaved end facets **369** and **371**. Wavelength tuning and far field beam steering can be accomplished by changing the current I_1 and I_2 applied to the waveguide sections **363** and **365**. If different currents I_1 and I_2 are applied simultaneously, the laser output is of tunable wavelength. As in previous embodiments the flared gain region **367** can be differentially pumped along its length with separate applied currents I_3 and I_4.

Referring to FIG. **31**, another flared laser oscillator **373** also has multiple single mode waveguide sections **375**, **377** and **379** feeding through a single mode combining section **381** to a common flared gain region **383**. However, grating reflectors **385**–**387** having grating pitches A_1, A_2 and A_3 and placed in the light path, here at the rear ends of the single mode waveguide sections **375**, **377** and **379**, are used to select the wavelengths of the laser output. The resonant cavity is defined by the gratings **385**–**387** and the low reflectivity front end facet **389**. The rear facet **390** may be oriented at a nonperpendicular angle to the direction of light propagation in order to suppress possible Fabry-Perot modes of oscillation. Different currents I_1–I_5 may be applied to respective sections **375**, **377**, **379**, **331** and **383**. Excitation of the various sections with currents of I_1, I_2 or I_3 also results in discrete switching of output wavelengths.

We claim:

1. A semiconductor laser comprising:

a multimode region having a gain portion, permitting therein propagation of light with a diverging phase front along the entire length of said multimode region toward an output surface,

optical feedback means for establishing a resonant optical cavity for the light propagating within said region, light propagating in said multimode region with said diverging phase front being fed back by said optical feedback means,

at least one single mode region at least partially within said cavity, and

a width of said multimode region at one end adjacent a corresponding end of said single mode region having a width greater than said single mode region one end, such that said single mode region is coupled through a step in width to said multimode region.

2. The semiconductor laser of claim **1** wherein said multimode region is a fared region extending from said multimode region one end.

3. The semiconductor laser of claim **1** wherein said optical feedback means comprises cleaved facets at opposite ends of said established resonant optical cavity.

4. The semiconductor laser of claim **1** wherein said feedback means comprises a combination of a cleaved facet and a grating.

5. The semiconductor laser of claim **1** further comprising means for differentially pumping at least a portion of said multimode region.

6. The semiconductor laser of claim **1** further comprising a diamond heat sink at least adjacent to a portion of said multimode region.

7. The semiconductor laser of claim **1** further comprising a flared region formed at the other end of said single mode region having a taper converging down to the width of said single mode region for coupling propagating light into said single mode region.

8. The semiconductor laser of claim **1** wherein said laser is wavelength tunable.

9. The semiconductor laser of claim **8** wherein said wavelength is electronically tunable.

10. The semiconductor laser of claim **1** further comprising means for mode locking said resonant optical cavity.

11. The semiconductor laser of claim **1** further comprising a lens system for imaging a point source of said diverging phase front emanating from said multimode region.

12. The semiconductor laser of claim **1** wherein a portion of the length of said single mode region proximate to said

single mode region one end is tapered toward said multimode region one end.

13. The semiconductor laser of claim **12** wherein said multimode region is a flared region extending from said multimode region one end.

14. The semiconductor laser of claim **12** wherein said optical feedback means comprises cleaved facets at opposite ends of said established resonant optical cavity.

15. The semiconductor laser of claim **12** wherein said feedback means comprises a combination of a cleaved facet and a grating.

16. The semiconductor laser of claim **12** further comprising means for differentially pumping at least a portion of said multimode region.

17. The semiconductor laser of claim **12** further comprising a diamond heat sink at least adjacent to a portion of said multimode region.

18. The semiconductor laser of claim **12** further comprising a flared region formed at the other end of said single mode region having a taper converging down to the width of said single mode region for coupling propagating light into said single mode region.

19. The semiconductor laser of claim **12** wherein said laser is wavelength tunable.

20. The semiconductor laser of claim **19** wherein said wavelength is electronically tunable.

21. The semiconductor laser of claim **12** further comprising means for mode locking said resonant optical cavity.

22. The semiconductor laser of claim **12** further comprising a lens system for imaging a point source of said diverging phase front emanating from said multimode region.

23. The semiconductor laser of claim **1** wherein said multimode region permitting said light propagation with said diverging phase front and said single mode region and said optical feedback means together define an unstable resonator cavity.

24. A semiconductor laser comprising:

a multimode region having a gain portion, said multimode region permitting therein propagation of light with a diverging phase front,

a single mode region having a length and a defined predominant width, said single mode region having one end thereof coupled to one end of said multimode region, wherein said single mode region has a narrower width dimension than said predominant width along a portion of the length of said single mode region that is adjacent to said multimode region one end, and

optical feedback means for establishing a resonant optical cavity for the light propagating within both said regions.

25. The semiconductor laser of claim **24** wherein said multimode region is a flared region extending from said multimode region one end.

26. The semiconductor laser of claim **24** wherein said optical feedback means comprises cleaved facets at opposite so ends of said established resonant optical cavity.

27. The semiconductor laser of claim **24** wherein said feedback means comprises a combination of a cleaved facet and a grating.

28. The semiconductor laser of claim **24** further comprising means for differentially pumping at least a portion of said multimode region.

29. The semiconductor laser of claim **24** further comprising a diamond heat sink at least adjacent to a portion of said multimode region.

30. The semiconductor laser of claim **24** further comprising a flared region formed at the other end of said single mode region having a taper converging down to the width of said single mode region for coupling propagating light into said single mode region.

31. The semiconductor laser of claim **24** wherein said laser is wavelength tunable.

32. The semiconductor laser of claim **31** wherein said wavelength is electronically tunable.

33. The semiconductor laser of claim **24** further comprising means for mode locking said resonant optical cavity.

34. The semiconductor laser of claim **24** further comprising a lens system for imaging a point source of said diverging phase front emanating from said multimode region.

35. The semiconductor laser of claim **24** wherein said multimode region is a gain guiding region.

36. A semiconductor laser comprising:

a flared region, at least a portion of which is capable of providing gain, permitting propagation of light with a diverging phase front therein,

means for providing feedback of light into said flared region to define a resonant optical cavity, and

a single mode light aperture region at least partially located within said cavity, wherein a narrow end of said flared region is wider than a corresponding end of said single mode light aperture region such that said single mode *light aperture* region is coupled through a step in width to said **[**multimode**]** *flared* region.

37. A semiconductor laser comprising:

a multimode region having a gain portion, said multimode region permitting propagation of light therein with a diverging phase front,

a single mode region having a length and a defined predominant width, said single mode region having one end thereof coupled to one end of said multimode region, wherein said single mode region has a narrower width dimension than said predominant at width along a portion of the length of said single mode region that is adjacent to said multimode region one end, and wherein said multimode region at said one end adjacent to said single mode region has a width greater than said narrower width dimension of said portion of said single mode region, such that said single mode region is coupled through a step in width to said multimode region, and

optical feedback means for establishing a resonant optical cavity including at least portions of said single mode region and said multimode region, light propagating in said multimode region with said diverging phase front being fed back by said optical feedback means toward said step in width and said narrower width portion of said single mode region.

38. A semiconductor laser device comprising

a single mode region coupled through a step in width into a broad gain region that permits lightwaves to propagate with a diverging phase front therein, an end of said broad gain region that is coupled to said single mode region having a greater width than a width of said single mode region,

means for providing optical feedback to said single mode and broad gain regions, lightwaves fed back in said broad gain region continuing to propagate with a diverging phase front therein toward the stepped end that is coupled to said single mode region and

means for coupling lightwaves out of said laser device from said broad gain region.

39. The laser device of claim **38** wherein said broad gain region is a flared region with a lateral dimension that increases from a narrower end coupled to said single mode region to a broader output end of said broad gain region.

40. The semiconductor laser of claim 36 wherein said means for providing feedback comprises cleaved facets at opposite ends of said resonant optical cavity.

41. The semiconductor laser of claim 36 wherein said means for providing feedback comprises a combination of a cleaved facet and a grating.

42. The semiconductor laser of claim 36 further comprising means for differentially pumping at least a portion of said flared region.

43. The semiconductor laser of claim 36 further comprising a diamond heat sink at least adjacent to a portion of said flared region.

44. The semiconductor laser of claim 36 further comprising a second flared region formed at the other end of said single mode light aperture region having a taper converging down to the width of said single mode light aperature region for coupling propagating light into said single mode light aperature region.

45. The semiconductor laser of claim 36 wherein said laser is wavelength tunable.

46. The semiconductor laser of claim 45 wherein said wavelength is electronically tunable.

47. The semiconductor laser of claim 36 further comprising means for mode locking said resonant optical cavity.

48. The semiconductor laser of claim 36 further comprising a lens system for imaging a point source of said diverging phase front emanating from said flared region.

49. The semiconductor laser of claim 36 wherein a portion of the length of said single mode light aperature region proximate to said corresponding end of said single mode light aperature region is tapered toward said narrow end of said flared region.

50. The semiconductor laser of claim 49 wherein said means for providing feedback comprises cleave facets at opposite ends of said resonant optical cavity.

51. The semiconductor laser of claim 49 wherein said means for providing feedback comprises a combination of a cleaved facet and a grating.

52. The semiconductor laser of claim 49 further comprising means for differentially pumping at least a portion of said flared region.

53. The semiconductor laser of claim 49 further comprising a diamond heat sink at least adjacent to a portion of said flared region.

54. The semiconductor laser of claim 49 further comprising a second flared region formed at the other end of said single mode light aperature region having a taper converging down to the width of said single mode light aperature region for coupling propagating light into said single mode light aperature region.

55. The semiconductor laser of claim 49 wherein said laser is wavelength tunable.

56. The semiconductor laser of claim 55 wherein said wavelength is electronically tunable.

57. The semiconductor laser of claim 49 further comprising means for mode locking said resonant optical cavity.

58. The semiconductor laser of claim 49 further comprising a lens system for imaging a point source of said diverging phase front emanating from said flared region.

59. The semiconductor laser of claim 36 wherein said flared region permitting said light propagation with said diverging phase front and said single mode light aperature region and said means for providing feedback together define an unstable resonator cavity.

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