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(54) **HIGH RESOLUTION THIN MULTI-APERTURE IMAGING SYSTEMS**

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(Continued)

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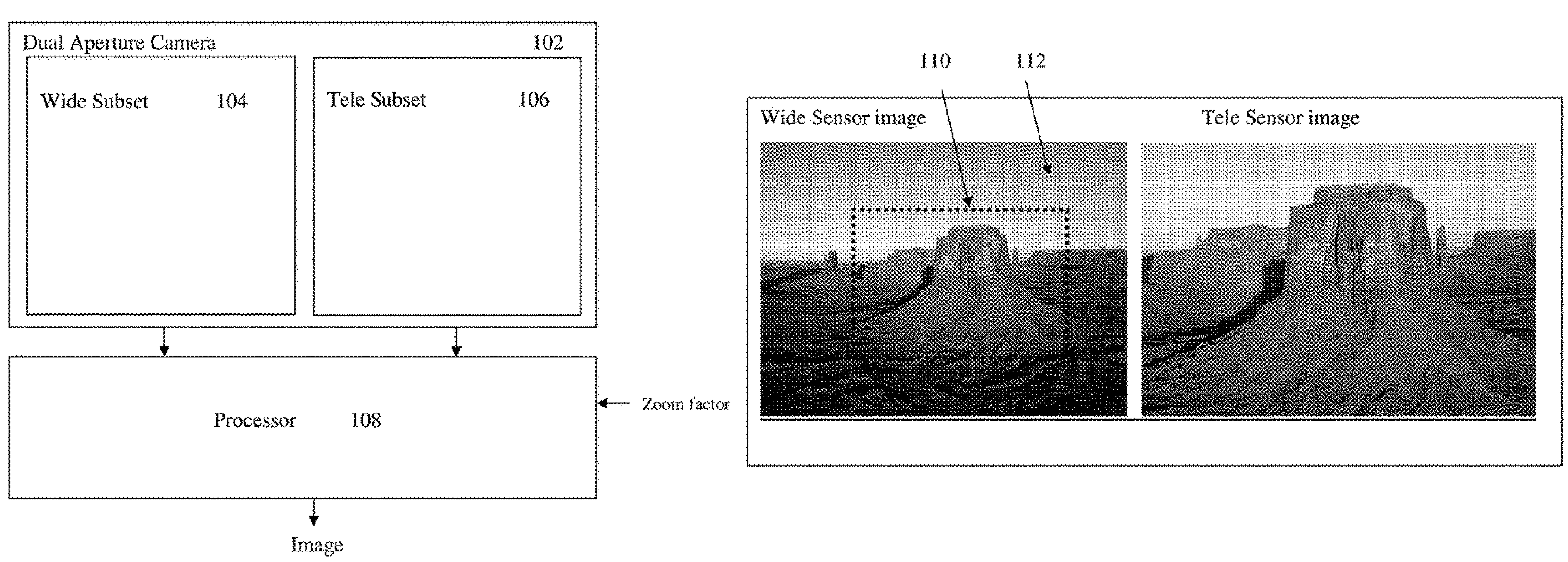
(57) **ABSTRACT**

A multi-aperture imaging system comprising a first camera with a first sensor that captures a first image and a second camera with a second sensor that captures a second image, the two cameras having either identical or different FOVs. The first sensor may have a standard color filter array (CFA) covering one sensor section and a non-standard color CFA covering another. The second sensor may have either Clear or standard CFA covered sections. Either image may be chosen to be a primary or an auxiliary image, based on a zoom factor. An output image with a point of view determined by the primary image is obtained by registering the auxiliary image to the primary image.

5 Claims, 7 Drawing Sheets

100



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See application file for complete search history.

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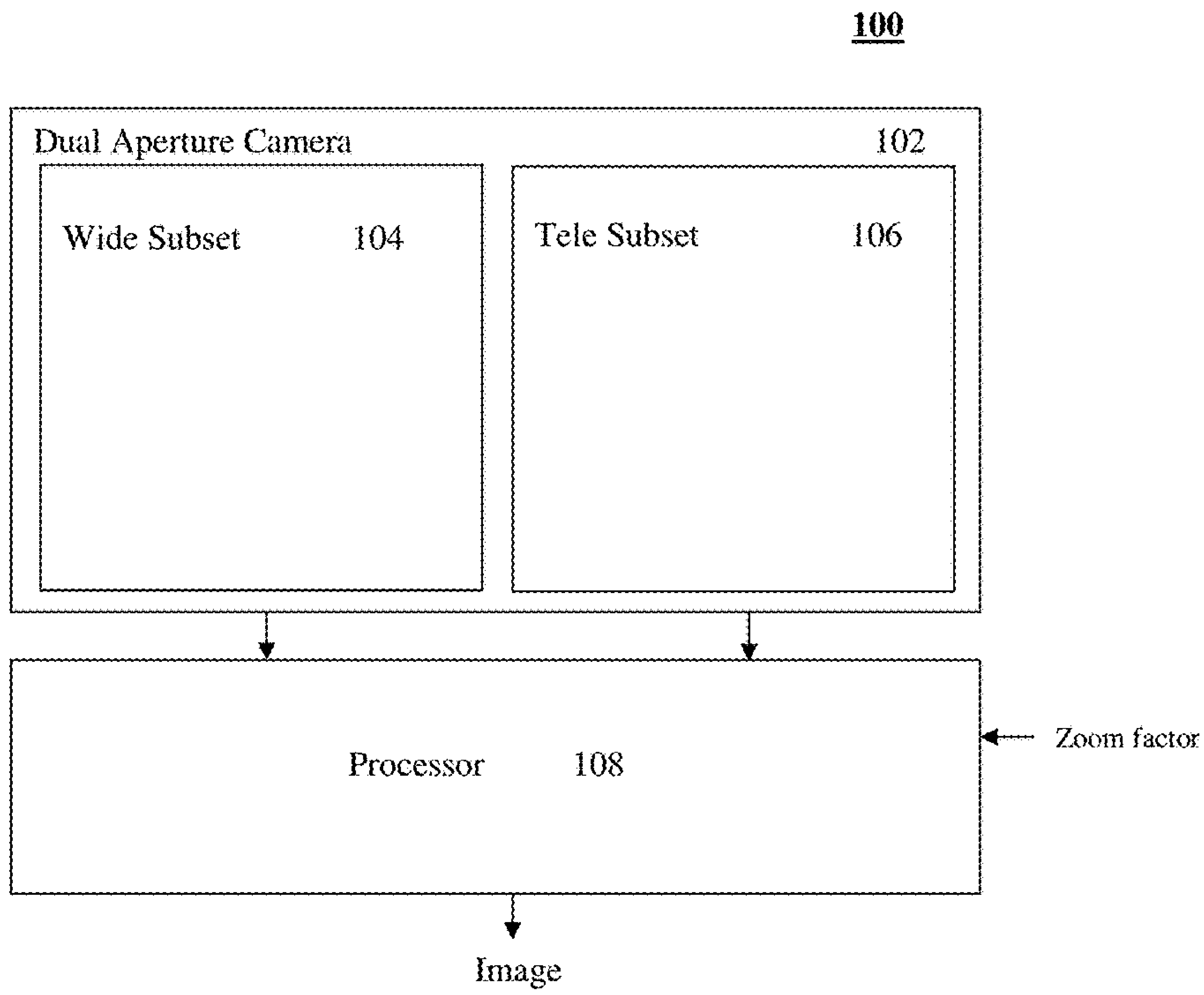

100
Dual Aperture Camera
102
Wide Subset
104
Tele Subset
106
Processor
108
Zoom factor
Image

FIG. 1A

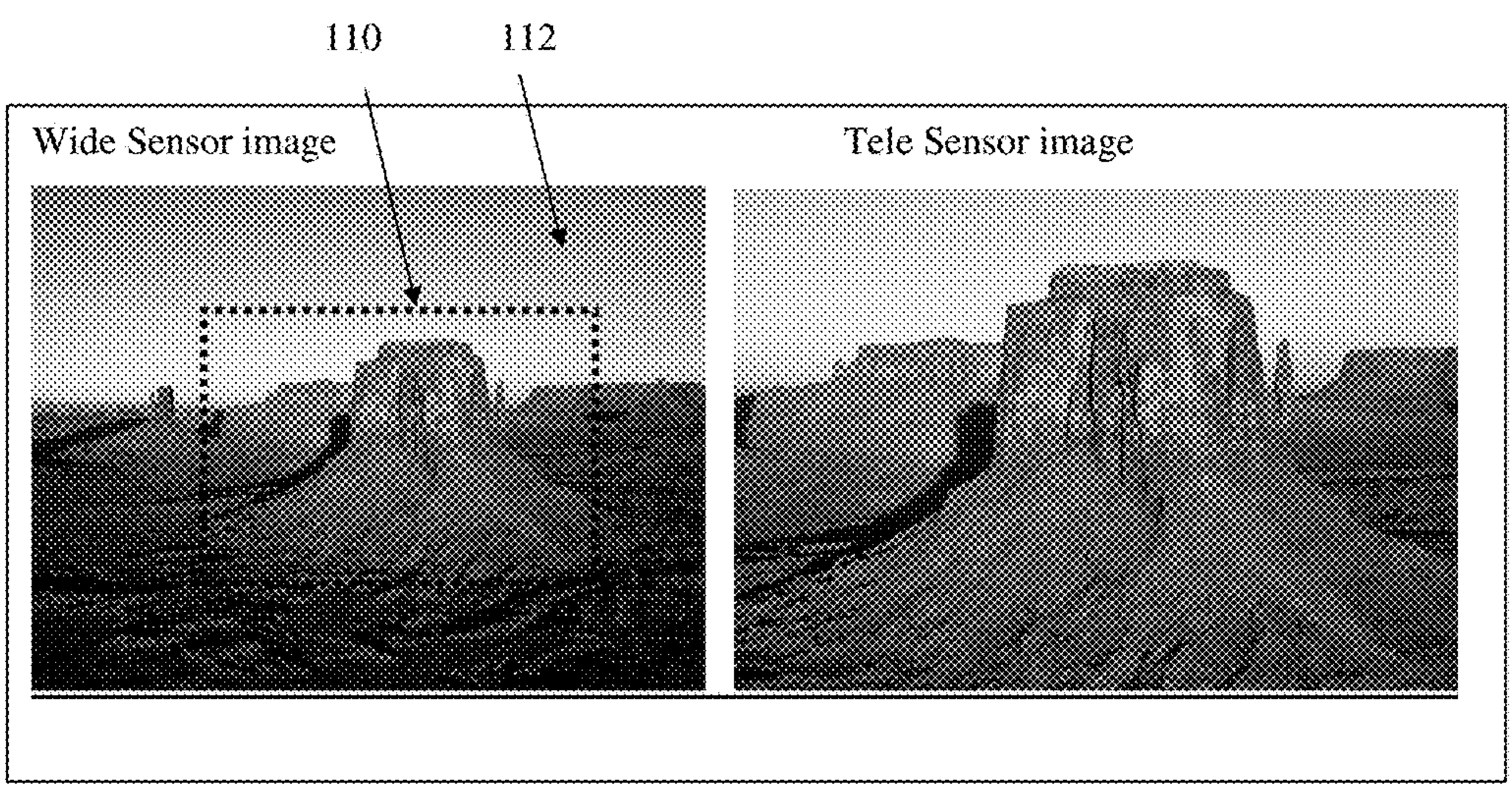

110
112
Wide Sensor image
Tele Sensor image

FIG. 1B

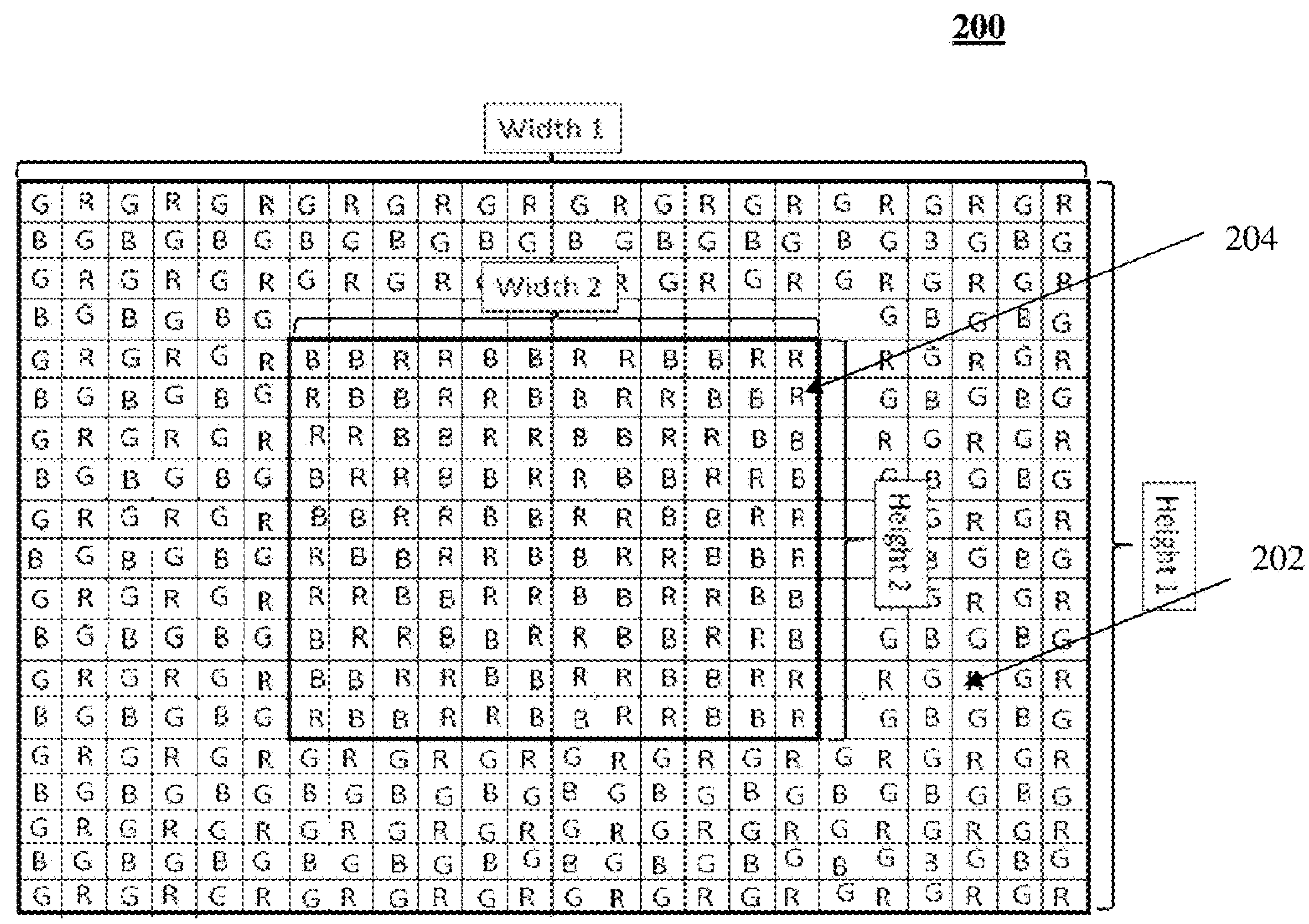

200
Width 1
Width 2
Height 2
Height 1
204
202

FIG. 2

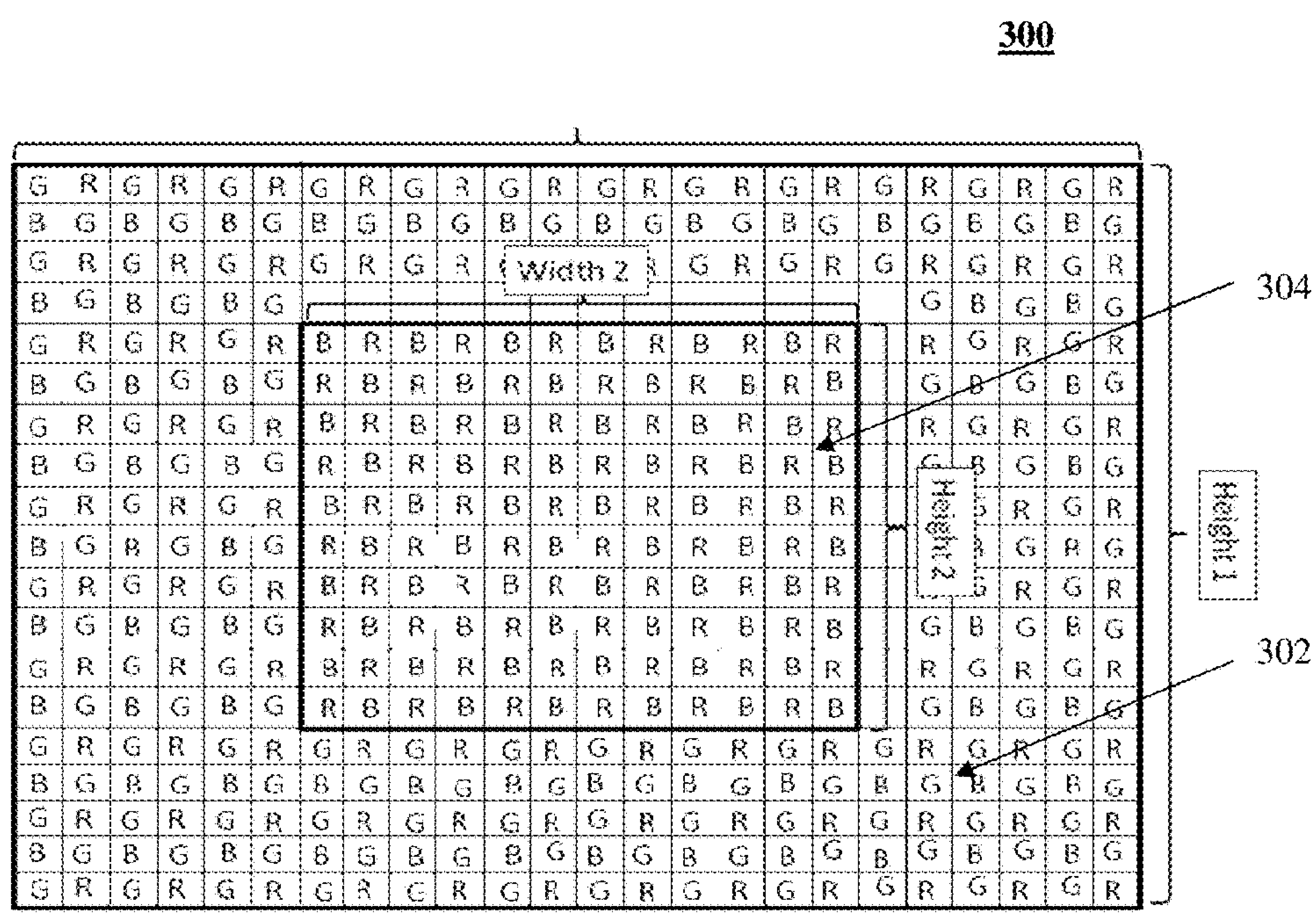

300
Width 2
Height 2
Height 1
304
302

FIG. 3

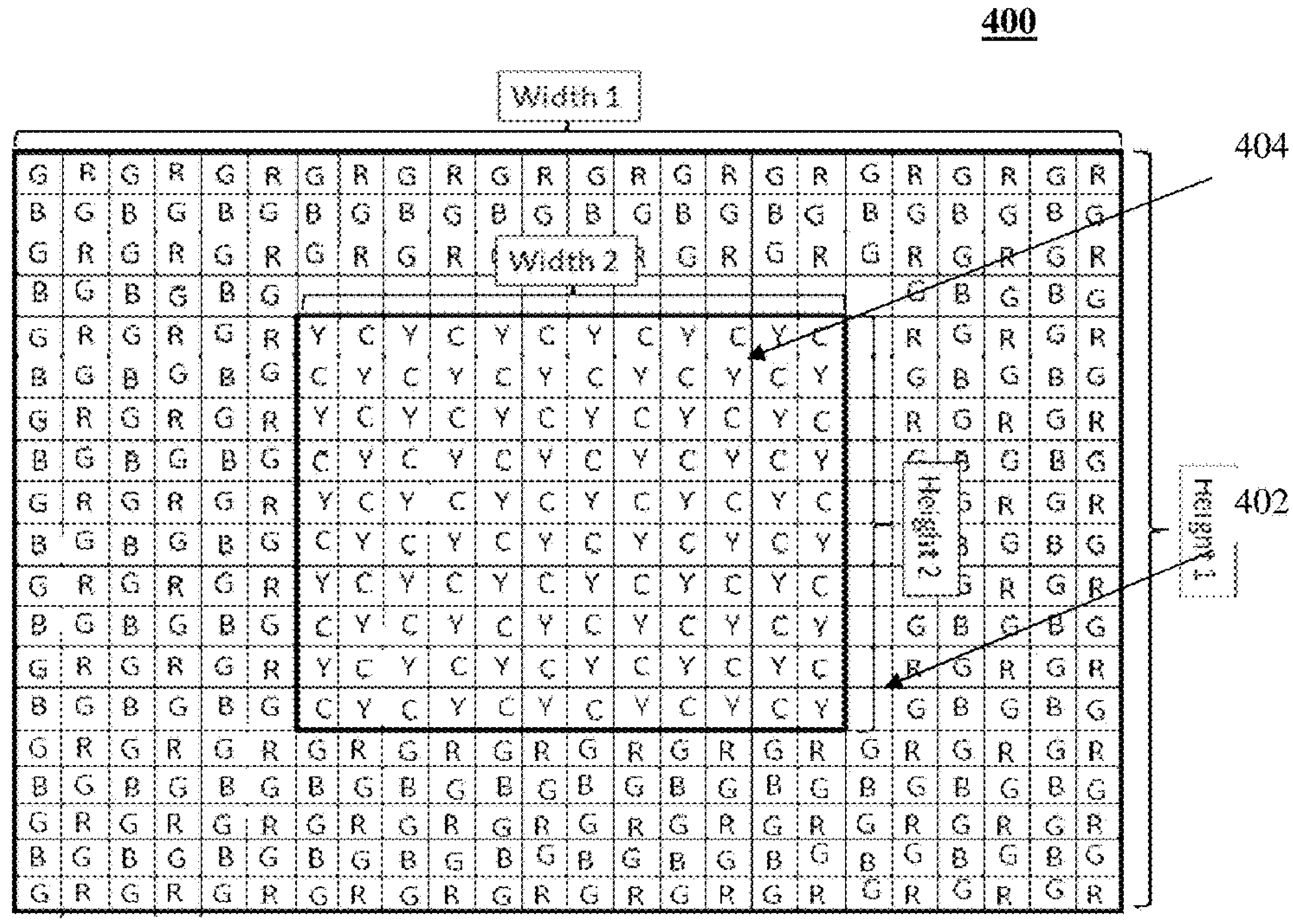

400
Width 1
Width 2
404
402
Height 2
Height 1

FIG. 4

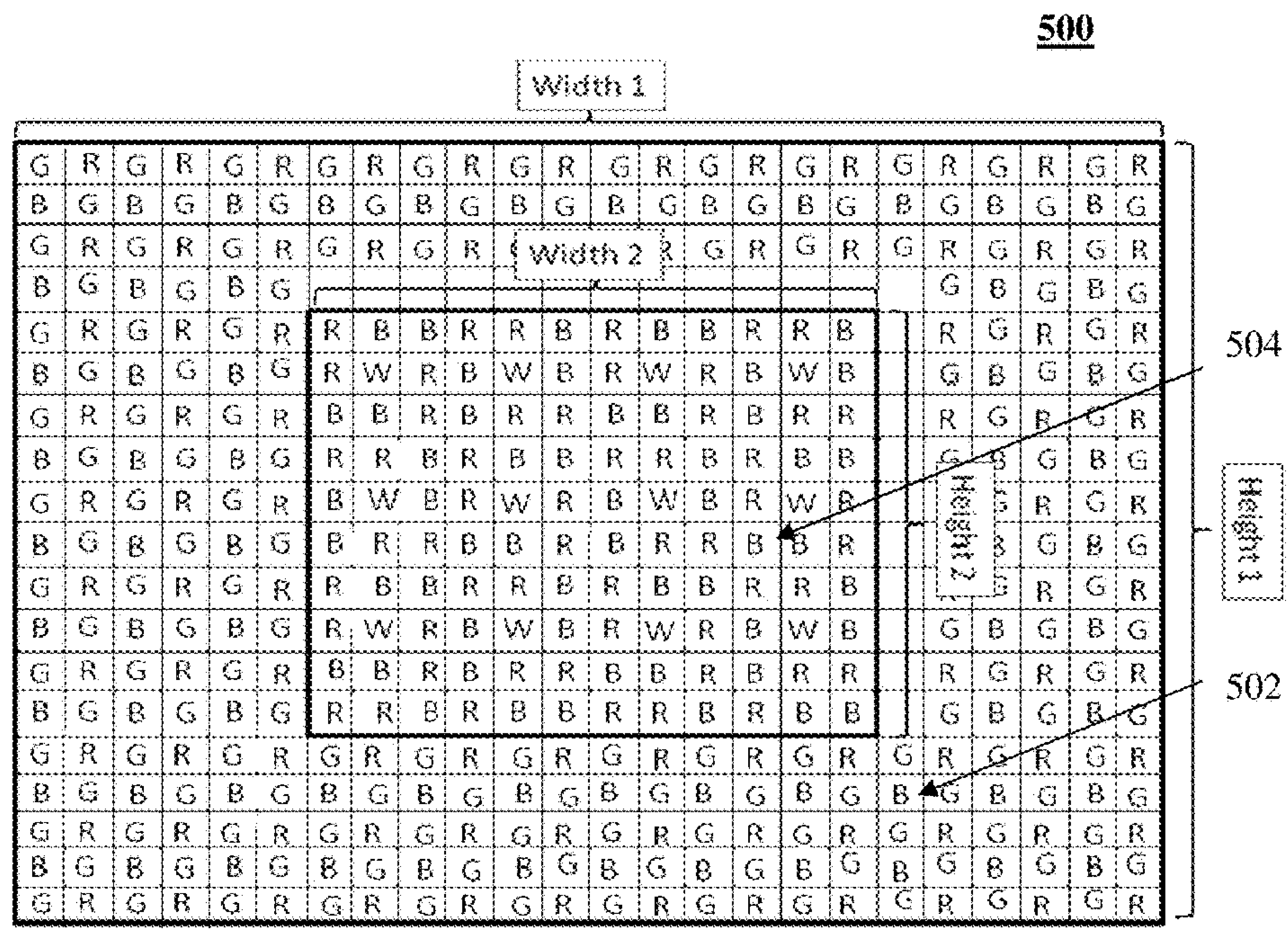

500
Width 1
Width 2
504
502
Height 2
Height 1

FIG. 5

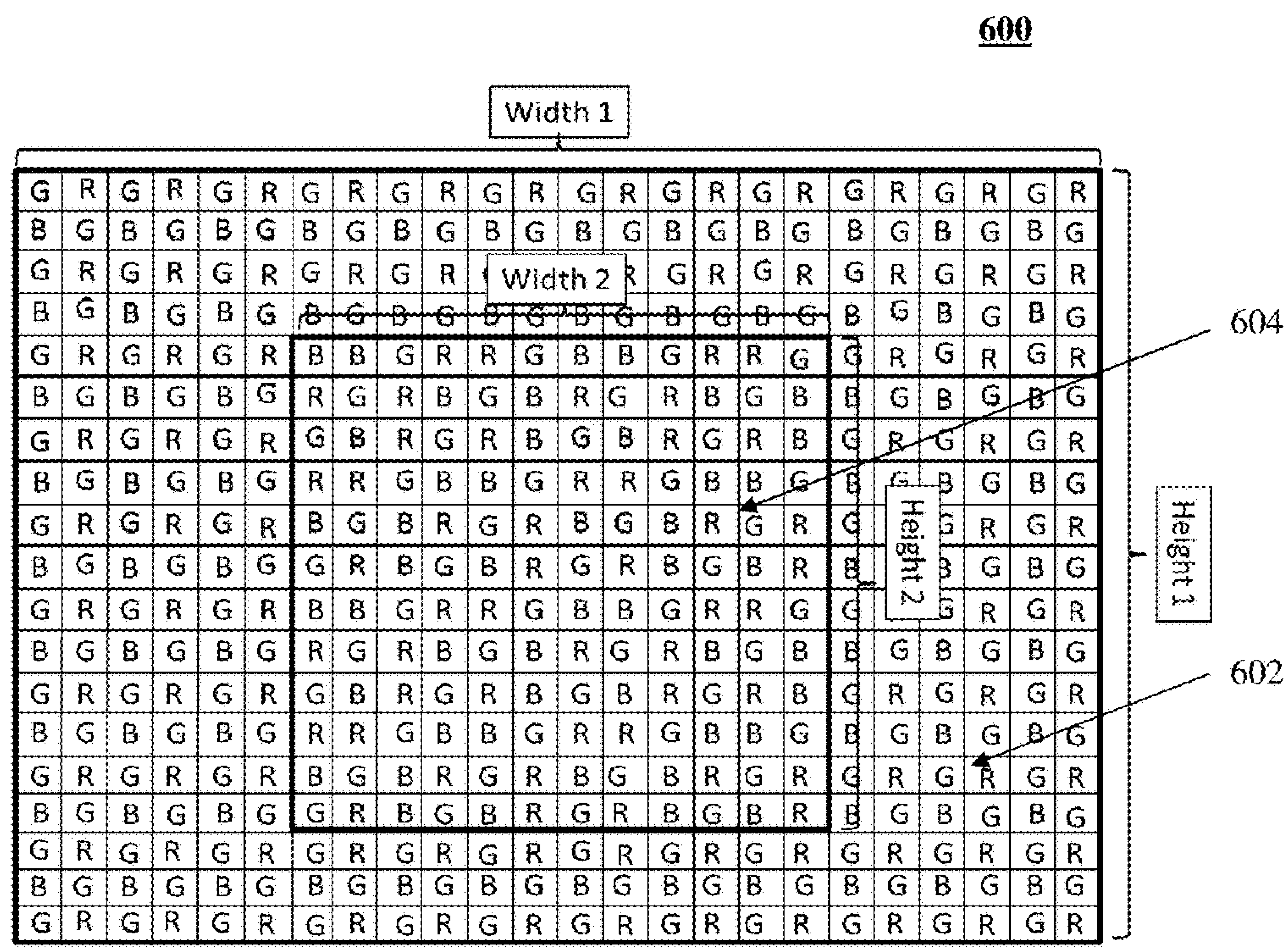

600
Width 1
Width 2
Height 1
Height 2
604
602

FIG. 6

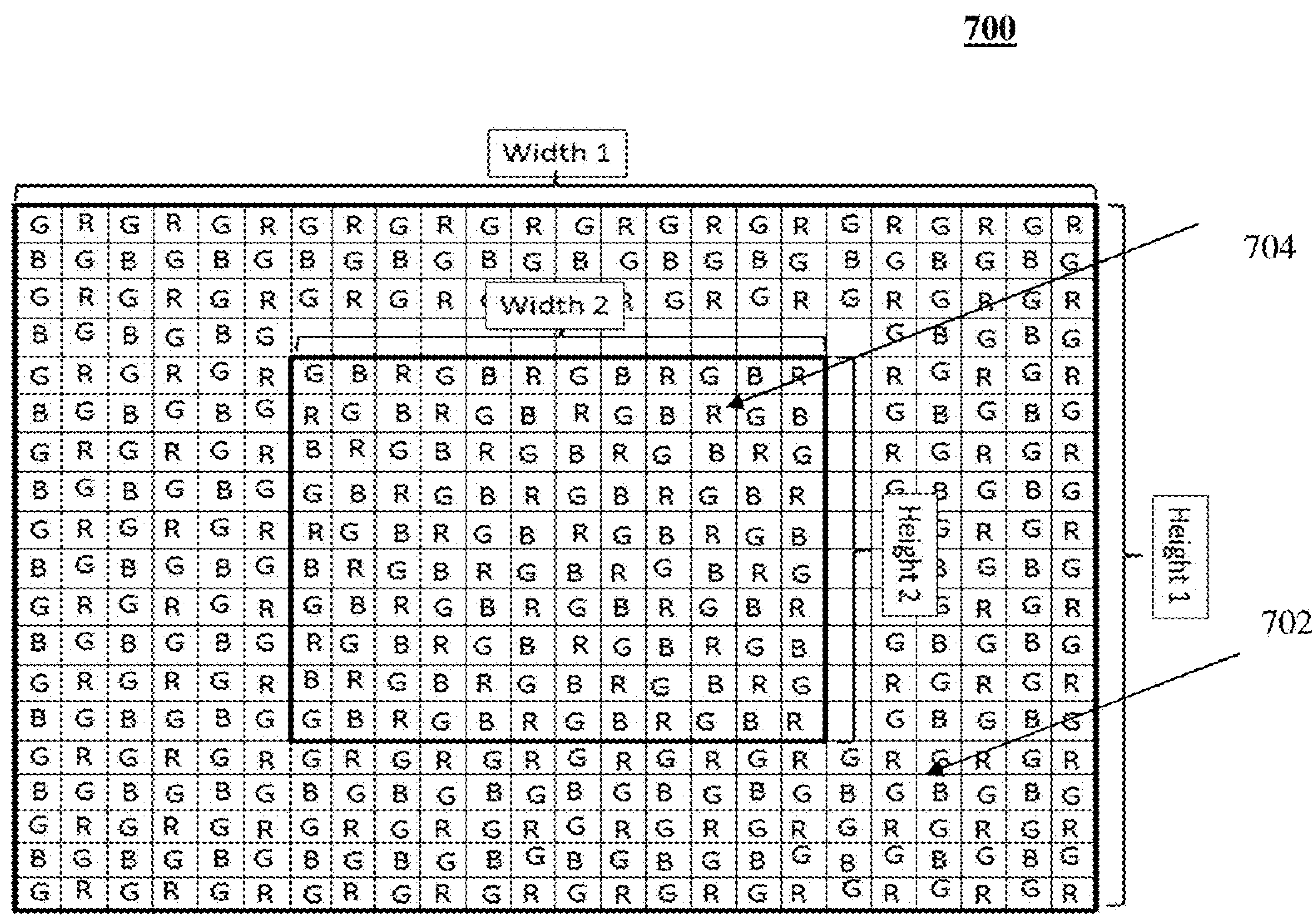

700
Width 1
Width 2
Height 1
Height 2
704
702

FIG. 7

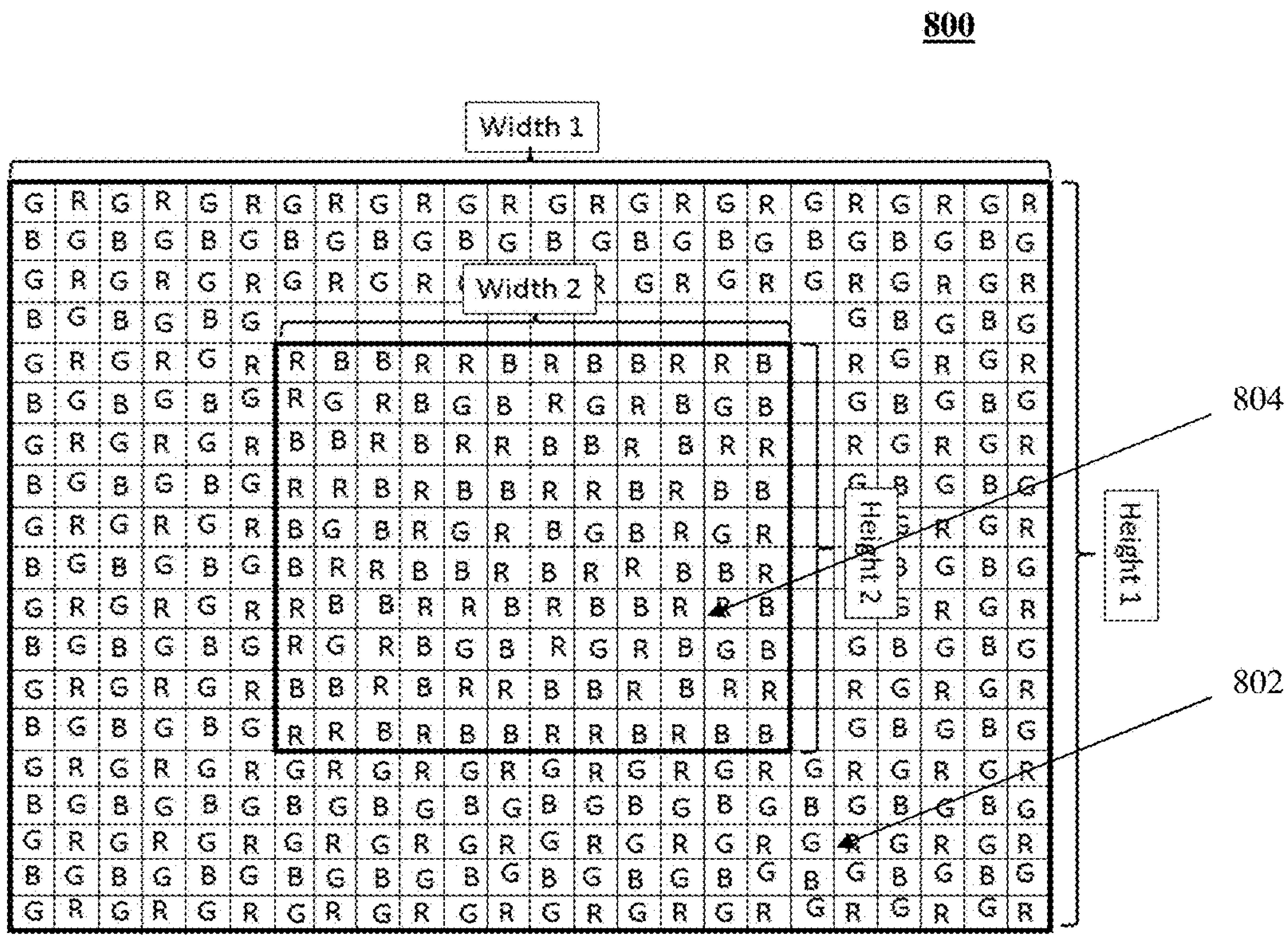

800
Width 1
Width 2
Height 2
Height 1
804
802

FIG. 8

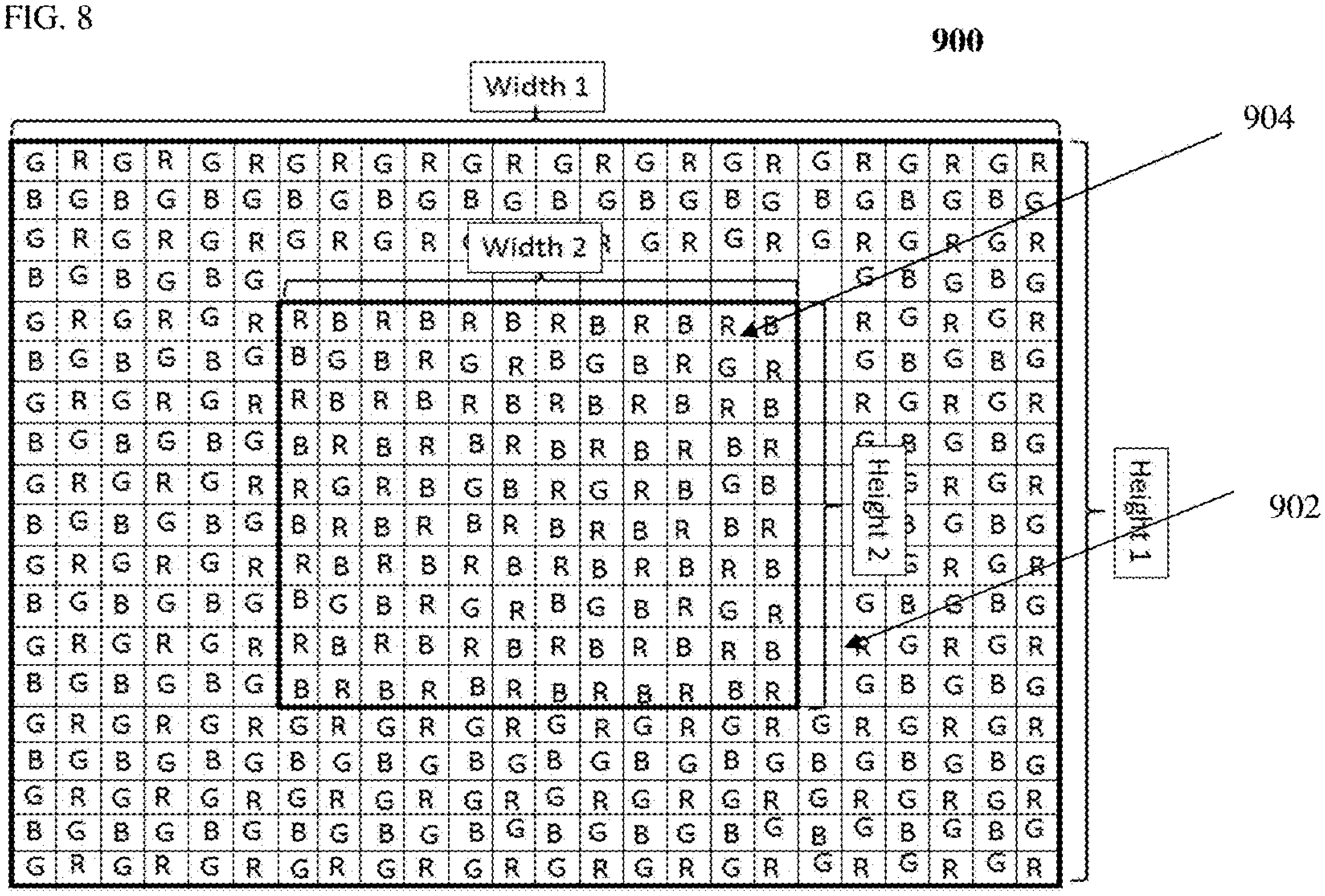
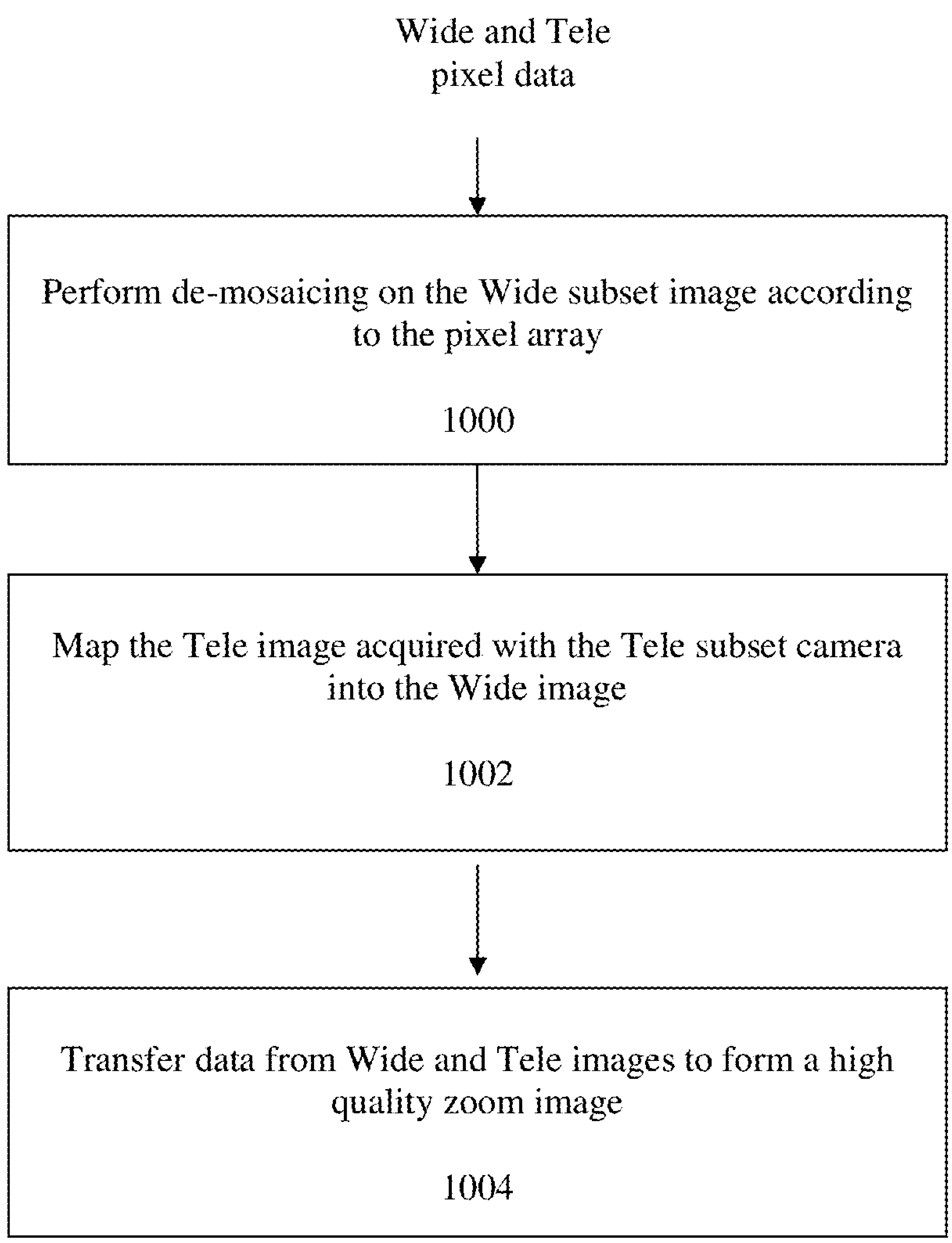

900
Width 1
Width 2
Height 2
Height 1
904
902

FIG. 9



Wide and Tele pixel data
Perform de-mosaicing on the Wide subset image according to the pixel array
1000
Map the Tele image acquired with the Tele subset camera into the Wide image
1002
Transfer data from Wide and Tele images to form a high quality zoom image
1004

FIG. 10

1100

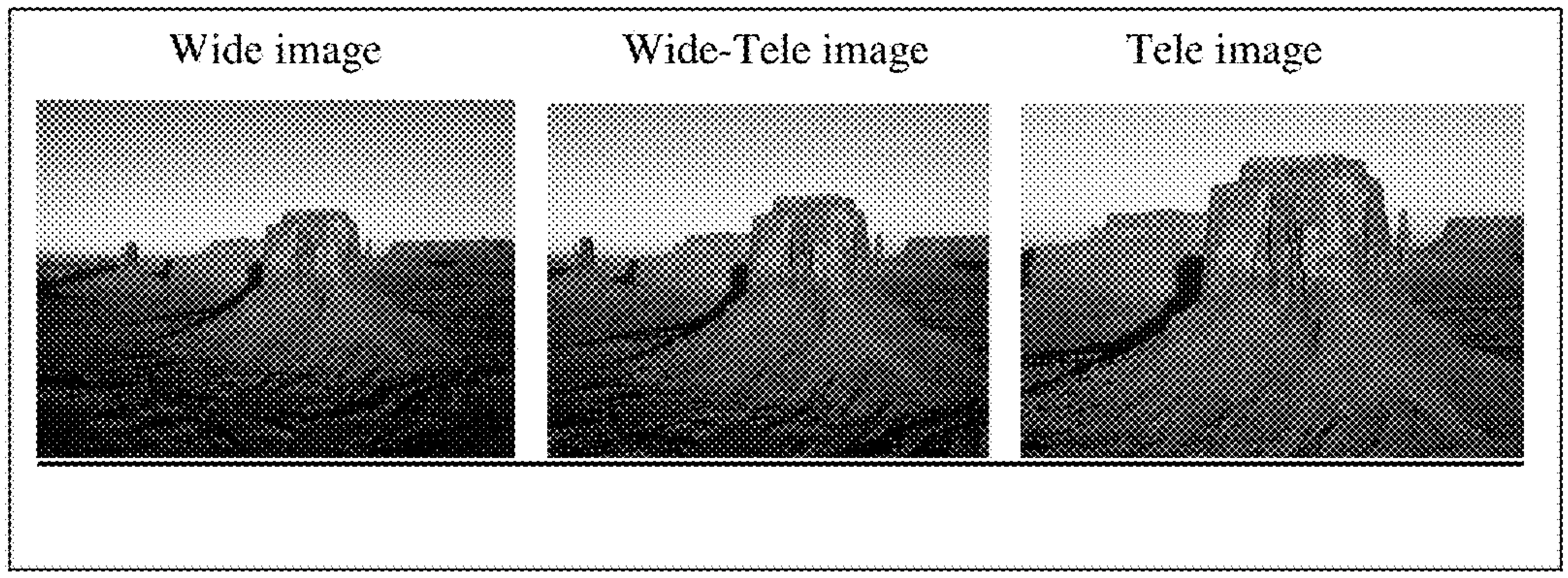


FIG. 11A

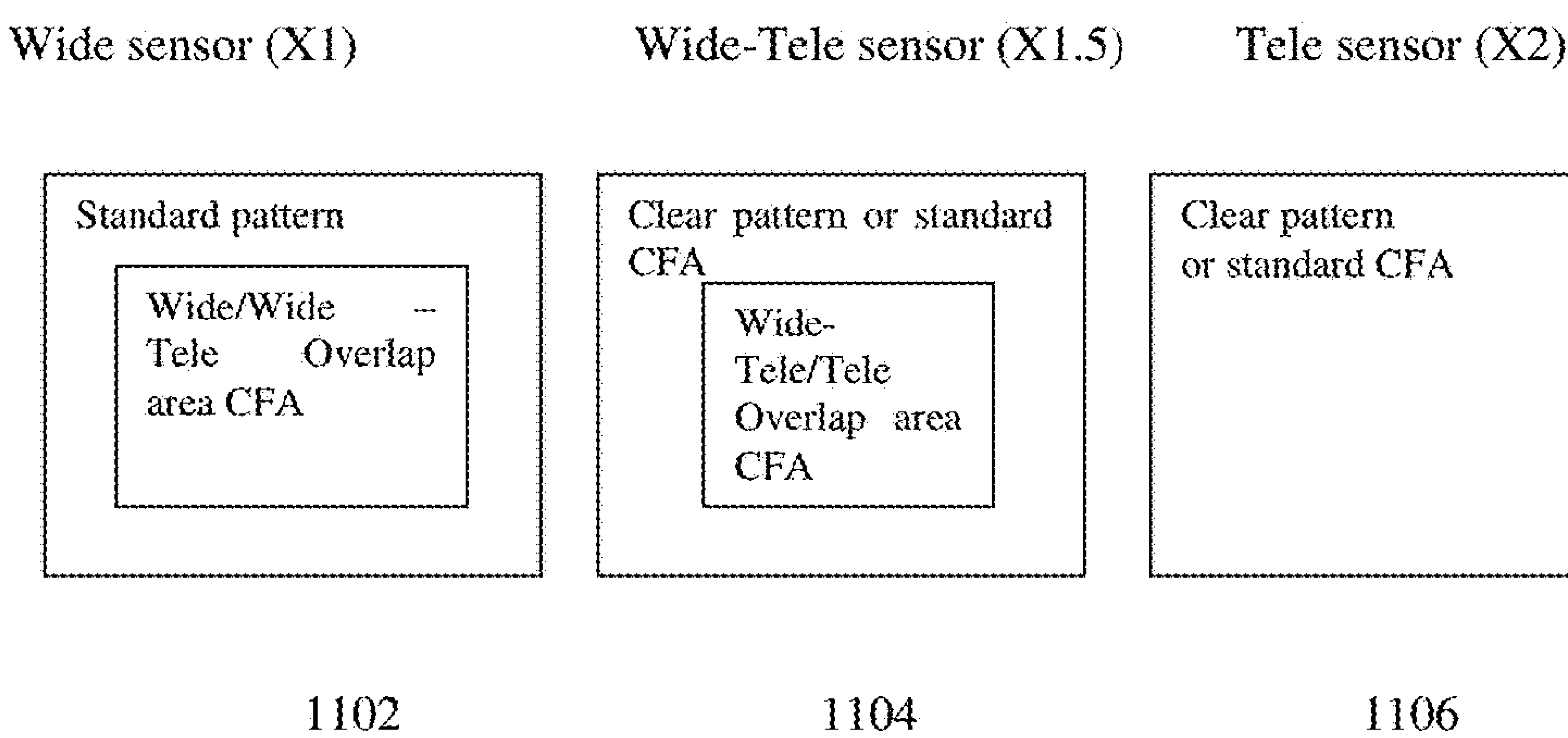


FIG. 11B

HIGH RESOLUTION THIN MULTI-APERTURE IMAGING SYSTEMS

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; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS REFERENCE TO RELATED APPLICATIONS

[This application is a Continuation application of U.S. patent application Ser. No. 14/386,823 (now allowed), which was a National Phase application from PCT patent application PCT/IB2013/060356 which claimed priority from U.S. Provisional Patent Application No. 61/730,570 having the same title and filed Nov. 28, 2012, the latter incorporated herein by reference in its entirety.] *This broadening reissue application is a continuation of U.S. patent application Ser. No. 16/383,618, filed Apr. 14, 2019, now U.S. Pat. No. RE48,4544E, which is a reissue application of U.S. patent application Ser. No. 15/375,090, filed Dec. 11, 2016, now U.S. Pat. No. 9,876,952, which is a continuation of U.S. patent application Ser. No. 14/386,823, filed Apr. 22, 2014, now U.S. Pat. No. 9,538,152, which was a National Phase application from PCT application PCT/IB2013/060356 which claimed priority from U.S. Provisional Patent Application No. 61/730,570 having the same title and filed Nov. 28, 2012, the latter incorporated herein by reference in its entirety. The following three co-pending applications are also continuation reissue applications of U.S. patent application Ser. No. 16/383,618, filed Apr. 14, 2019: U.S. patent application Ser. No. 16/384,140, filed Apr. 15, 2019, U.S. patent application Ser. No. 16/384,197, filed Apr. 15, 2019, and U.S. patent application Ser. No. 16/384,244, filed Apr. 15, 2019.*

FIELD

Embodiments disclosed herein relate in general to multi-aperture imaging ("MAI") systems (where "multi" refers to two or more apertures) and more specifically to thin MAI systems with high color resolution and/or optical zoom.

BACKGROUND

Small digital cameras integrated into mobile (cell) phones, personal digital assistants and music players are becoming ubiquitous. Each year, mobile phone manufacturers add more imaging features to their handsets, causing these mobile imaging devices to converge towards feature sets and image quality that customers expect from stand-alone digital still cameras. Concurrently, the size of these handsets is shrinking, making it necessary to reduce the total size of the camera accordingly while adding more imaging features. Optical Zoom is a primary feature of many digital still cameras but one that mobile phone cameras usually lack, mainly due to camera height constraints in mobile imaging devices, cost and mechanical reliability.

Mechanical zoom solutions are common in digital still cameras but are typically too thick for most camera phones. Furthermore, the F/# ("F number) in such systems typically increases with the zoom factor (ZF) resulting in poor light sensitivity and higher noise (especially in low-light sce-

narios). In mobile cameras, this also results in resolution compromise, due to the small pixel size of their image sensors and the diffraction limit optics associated with the F/#.

One way of implementing zoom in mobile cameras is by over-sampling the image and cropping and interpolating it in accordance with the desired ZF. While this method is mechanically reliable, it results in thick optics and in an expensive image sensor due to the large number of pixels so associated therewith. As an example, if one is interested in implementing a 12 Megapixel camera with X3 ZF, one needs a sensor of 108 Megapixels.

Another way of implementing zoom, as well as increasing the output resolution, is by using a dual-aperture imaging ("DAI") system. In its basic form, a DAI system includes two optical apertures which may be formed by one or two optical modules, and one or two image sensors (e.g., CMOS or CCD) that grab the optical image or images and convert the data into the electronic domain, where the image can be processed and stored.

The design of a thin MAI system with improved resolution requires a careful choice of parameters coupled with advanced signal processing algorithms to support the output of a high quality image. Known MAI systems, in particular ones with short optical paths, often trade-off functionalities and properties, for example zoom and color resolution, or image resolution and quality for camera module height. Therefore, there is a need for, and it would be advantageous to have thin MAI systems that produce an image with high resolution (and specifically high color resolution) together with zoom functionality.

Moreover, known signal processing algorithms used together with existing MAI systems often further degrade the output image quality by introducing artifacts when combining information from different apertures. A primary source of these artifacts is the image registration process, which has to find correspondences between the different images that are often captured by different sensors with different color filter arrays (CFAs). There is therefore a need for, and it would be advantageous to have an image registration algorithm that is more robust to the type of CFA used by the cameras and which can produce better correspondence between images captured by a multi-aperture system.

SUMMARY

Embodiments disclosed herein teach the use of multi-aperture imaging systems to implement thin cameras (with short optical paths of less than about 9 mm) and/or to realize optical zoom systems in such thin cameras. Embodiments disclosed herein further teach new color filter arrays that optimize the color information which may be achieved in a multi-aperture imaging system with or without zoom. In various embodiments, a MAI system disclosed herein includes at least two sensors or a single sensor divided into at least two areas. Hereinafter, the description refers to "two sensors", with the understanding that they may represent sections of a single physical sensor (imager chip). Exemplarily, in a dual-aperture imaging system, a left sensor (or left side of a single sensor) captures an image coming from a first aperture while a right sensor (or right side of a single sensor) captures an image coming from a second aperture. In various embodiments disclosed herein, one sensor is a "Wide" sensor while another sensor is a "Tele" sensor, see e.g. FIG. 1A. The Wide sensor includes either a single standard CFA or two different CFAs: a non-standard CFA with higher color sampling rate positioned in an "overlap

area" of the sensor (see below description of FIG. 1B) and a standard CFA with a lower color sampling rate surrounding the overlap area. When including a single standard CFA, the CFA may cover the entire Wide sensor area. A "standard CFA" may include a RGB (Bayer) pattern or a non-Bayer pattern such as RGBE, CYYM, CYGM, RGBW#1, RGBW#2 or RGBW#3. Thus, reference may be made to "standard Bayer" or "standard non-Bayer" patterns or filters. As used herein, "non-standard CFA" refers to a CFA that is different in its pattern that CFAs listed above as "standard". Exemplary non-standard CFA patterns may include repetitions of a 2×2 micro-cell in which the color filter order is RR-BB, RB-BR or YC-CY where Y=Yellow=Green+Red, C=Cyan=Green+Blue; repetitions of a 3×3 micro-cell in which the color filter order is GBR-RGB-BRG; and repetitions of a 6×6 micro-cell in which the color filter order is RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, or BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR, or RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR, or, RBRBRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR.

The Tele sensor may be a Clear sensor (i.e. a sensor without color filters) or a standard CFA sensor. This arrangement of the two (or more than two) sensors and of two (or more than two) Wide and Tele "subset cameras" (or simply "subsets") related to the two Wide and Tele subsets. Each sensor provides a separate image (referred to respectively as a Wide image and a Tele image), except for the case of a single sensor, where two images are captured (grabbed) by the single sensor (example above). In some embodiments, zoom is achieved by fusing the two images, resulting in higher color resolution that approaches that of a high quality dual-aperture zoom camera. Some thin MAI systems disclosed herein therefore provide zoom, super-resolution, high dynamic range and enhanced user experience.

In some embodiments, in order to reach optical zoom capabilities, a different magnification image of the same scene is grabbed by each subset, resulting in field of view (FOV) overlap between the two subsets. In some embodiments, the two subsets have the same zoom (i.e. same FOV). In some embodiments, the Tele subset is the higher zoom subset and the Wide subset is the lower zoom subset. Post processing is applied on the two images grabbed by the MAI system to fuse and output one fused (combined) output zoom image processed according to a user ZF input request. In some embodiments, the resolution of the fused image may be higher than the resolution of the Wide/Tele sensors. As part of the fusion procedure, up-sampling may be applied on the Wide image to scale it to the Tele image.

In an embodiment there is provided a multi-aperture imaging system comprising a first camera subset that provides a first image, the first camera subset having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard CFA, the non-standard CFA used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA; a second camera subset that provides a second image, the second camera subset having a second sensor with a second plurality of sensor pixels either Clear or covered with a standard CFA; and a processor configured to process the first and second images into a combined output image.

In some embodiments, the first and the second camera subsets have identical FOVs and the non-standard CFA may cover an overlap area that includes all the pixels of first sensor, thereby providing increased color resolution. In some such embodiments, the processor is further configured to, during the processing of the first and second images into a combined output image, register respective first and second Luma images obtained from the first and second images, the registered first and second Luma images used together with color information to form the combined output image. In an embodiment, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image, whereby the output image is formed by transferring information from the second image to the first image. In another embodiment, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, whereby the output image is formed by transferring information from the first image to the second image.

In some embodiments, the first camera subset has a first FOV, the second camera subset has a second, smaller FOV than the first FOV, and the non-standard CFA covers an overlap area on the first sensor that captures the second FOV, thereby providing both optical zoom and increased color resolution. In some such embodiments, the processor is further configured to, during the processing of the first and second images into a combined output image and based on a ZF input, register respective first and second Luma images obtained from the first and second images, the registered first and second Luma images used together with color information to form the combined output image. For a ZF input that defines an FOV greater than the second FOV, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image and the processing includes forming the output image by transferring information from the second image to the first image. For a ZF input that defines an FOV smaller than or equal to the second FOV, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, and the processing includes forming the output image by transferring information from the first image to the second image.

In an embodiment there is provided a multi-aperture imaging system comprising a first camera subset that provides a first image, the first camera subset having a first sensor with a first plurality of sensor pixels covered at least in part with a standard CFA; a second camera subset that provides a second image, the second camera subset having a second sensor with a second plurality of sensor pixels either Clear or covered with a standard CFA; and a processor configured to register first and second Luma images obtained respectively from the first and second images and to process the registered first and second Luma images together with color information into a combined output image.

In some embodiments, the first and the second camera subsets have identical first and second FOVs. In some such embodiments, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image and the processing includes forming the output image by transferring information from the second image to the first image. In other such embodiments, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image and the processing includes forming the output image by transferring information from the first image to the second image.

In some embodiments, the first camera subset has a first FOV, the second camera subset has a second, smaller FOV than the first FOV, and the processor is further configured to register the first and second Luma images based on a ZF input. For a ZF input that defines an FOV greater than the second FOV, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first

Luma image and the processing includes forming the output image by transferring information from the second image to the first image. For a ZF input that defines an FOV smaller than or equal to the second FOV, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, and the processing includes forming the output image by transferring information from the first image to the second image.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting examples of embodiments disclosed herein are described below with reference to figures attached hereto that are listed following this paragraph. The drawings and descriptions are meant to illuminate and clarify embodiments disclosed herein, and should not be considered limiting in any way.

FIG. **1**A shows schematically a block diagram illustrating a dual-aperture zoom imaging system disclosed herein;

FIG. **1**B shows an example of an image captured by the Wide sensor and the Tele sensor while illustrating the overlap area on the Wide sensor;

FIG. **2** shows schematically an embodiment of a Wide sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **3** shows schematically another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **4** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **5** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **6** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **7** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **8** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **9** shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. **10** shows a schematically in a flow chart an embodiment of a method disclosed herein for acquiring and outputting a zoom image;

FIG. **11**A shows exemplary images captured by a triple aperture zoom imaging system disclosed herein;

FIG. **11**B illustrates schematically the three sensors of the triple aperture imaging system of FIG. **11**A.

DETAILED DESCRIPTION

Embodiments disclosed herein relate to multi-aperture imaging systems that include at least one Wide sensor with a single CFA or with two different CFAs and at least one Tele sensor. The description continues with particular reference to dual-aperture imaging systems that include two (Wide and Tele) subsets with respective sensors. A three-aperture imaging system is described later with reference to FIGS. **11**A-**11**B.

The Wide sensor includes an overlap area (see description of FIG. **1**B) that captures the Tele FOV. The overlap area may cover the entire Wide sensor or only part of the sensor.

The overlap area may include a standard CFA or a non-standard CFA. Since the Tele image is optically magnified compared to the Wide image, the effective sampling rate of the Tele image is higher than that of the Wide image. Thus, the effective color sampling rate in the Wide sensor is much lower than the Clear sampling rate in the Tele sensor. In addition, the Tele and Wide images fusion procedure (see below) requires up-scaling of the color data from the Wide sensor. Up-scaling will not improve color resolution. In some applications, it is therefore advantageous to use a non-standard CFA in the Wide overlap area that increases color resolution for cases in which the Tele sensor includes only Clear pixels. In some embodiments in which the Tele sensor includes a Bayer CFA, the Wide sensor may have a Bayer CFA in the overlap area. In such embodiments, color resolution improvement depends on using color information from the Tele sensor in the fused output image.

FIG. **1**A shows schematically a block diagram illustrating a dual-aperture zoom imaging ("DAZI") system **100** disclosed herein. System **100** includes a dual-aperture camera **102** with a Wide subset **104** and a Tele subset **106** (each subset having a respective sensor), and a processor **108** that fuses two images, a Wide image obtained with the Wide subset and a Tele image obtained with the Tele subset, into a single fused output image according to a user-defined "applied" ZF input or request. The ZF is input to processor **108**. The Wide sensor may include a non-standard CFA in an overlap area illustrated by **110** in FIG. **1**B. Overlap area **110** is surrounded by a non-overlap area **112** with a standard CFA (for example a Bayer pattern). FIG. **1**B also shows an example of an image captured by both Wide and Tele sensors. Note that "overlap" and "non-overlap" areas refer to parts of the Wide image as well as to the CFA arrangements of the Wide sensor. The overlap area may cover different portions of a Wide sensor, for example half the sensor area, a third of the sensor area, a quarter of the sensor area, etc. A number of such Wide sensor CFA arrangements are described in more detail with reference to FIGS. **2**-**9**. The non-standard CFA pattern increases the color resolution of the DAZI system.

The Tele sensor may be Clear (providing a Tele Clear image scaled relative to the Wide image) or may include a standard (Bayer or non-Bayer) CFA. It in the latter case, it is desirable to define primary and auxiliary sensors based on the applied ZF. If the ZF is such that the output FOV is larger than the Tele FOV, the primary sensor is the Wide sensor and the auxiliary sensor is the Tele sensor. If the ZF is such that the output FOV is equal to, or smaller than the Tele FOV, the primary sensor is the Tele sensor and the auxiliary sensor is the Wide sensor. The point of view defined by the output image is that of the primary sensor.

FIG. **2** shows schematically an embodiment of a Wide sensor **200** that may be implemented in a DAZI system such as system **100**. Sensor **200** has a non-overlap area **202** with a Bayer CFA and an overlap area **204** covered by a non-standard CFA with a repetition of a 4×4 micro-cell in which the color filter order is BBRR-RBBR-RRBB-BRRB. In this figure, as well as in FIGS. **3**-**9**, "Width **1**" and "Height **1**" refer to the full Wide sensor dimension. "Width **2**" and "Height **2**" refer to the dimensions of the Wide sensor overlap area. Note that in FIG. **2** (as in following FIGS. **3**-**5** and **7**, **8**) the empty row and column to the left and top of the overlap area are for clarity purposes only, and that the sensor pixels follow there the pattern of the non-overlap area (as shown in FIG. **6**). In overlap area **204**, R and B are sampled at $\frac{1}{2}^{0.5}$ Nyquist frequency in the diagonal (left to right) direction with 2 pixel intervals instead of at ½ Nyquist frequency in a standard Bayer pattern.

FIG. **3** shows schematically an embodiment of a Wide sensor **300** that may be implemented in a DAZI system such as system **100**. Sensor **300** has a non-overlap area **302** with a Bayer CFA and an overlap area **304** covered by a non-standard CFA with a repetition of a 2×2 micro-cell in which the color filter order is BR-RB. In the overlap area, R and B are sampled at $½^{0.5}$ Nyquist frequency in both diagonal directions.

FIG. **4** shows schematically an embodiment of a Wide sensor **400** that may be implemented in a DAZI system such as system **100**. Sensor **400** has a non-overlap area **402** with a Bayer CFA and an overlap area **404** covered by a non-standard CFA with a repetition of a 2×2 micro-cell in which the color filter order is YC-CY, where Y=Yellow=Green+Red, C=Cyan=Green+Blue. As a result, in the overlap area, R and B are sampled at $½^{0.5}$ Nyquist frequency in a diagonal direction. The non-standard CFA includes green information for registration purposes. This allows for example registration between the two images where the object is green, since there is green information in both sensor images.

FIG. **5** shows schematically an embodiment of a Wide sensor **500** that may be implemented in a DAZI system such as system **100**. Sensor **500** has a non-overlap area **502** with a Bayer CFA and an overlap area **504** covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, where "W" represents White or Clear pixels. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in a Bayer pixel order, the Red average sampling rate ("R_s") is 0.25 (sampled once for every 4 pixels). In the overlap area pattern, R_s is 0.44.

FIG. **6** shows schematically an embodiment of a Wide sensor **600** that may be implemented in a DAZI system such as system **100**. Sensor **600** has a non-overlap area **602** with a Bayer CFA and an overlap area **604** covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.33 vs. 0.25 in a Bayer pixel order.

FIG. **7** shows schematically an embodiment of a Wide sensor **700** that may be implemented in a DAZI system such as system **100**. Sensor **700** has a non-overlap area **702** with a Bayer CFA and an overlap area **704** covered by a non-standard CFA with a repetition of a 3×3 micro-cell in which the color filter order is GBR-RGB-BRG. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.33 vs. 0.25 in a Bayer pixel order.

FIG. **8** shows schematically an embodiment of a Wide sensor **800** that may be implemented in a DAZI system such as system **100**. Sensor **800** has a non-overlap area **802** with a Bayer CFA and an overlap area **804** covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.44 vs. 0.25 in a Bayer pixel order.

FIG. **9** shows schematically an embodiment of a Wide sensor **900** that may be implemented in a DAZI system such as system **100**. Sensor **900** has a non-overlap area **902** with a Bayer CFA and an overlap area **904** covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBRBRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.44 vs. 0.25 in a Bayer pixel order.

Processing Flow

In use, an image is acquired with imaging system **100** and is processed according to steps illustrated in a flowchart shown in FIG. **10**. In step **1000**, demosaicing is performed on the Wide overlap area pixels (which refer to the Tele image FOV) according to the specific CFA pattern. If the CFA in the Wide overlap area is a standard CFA, a standard demosaicing process may be applied to it. If the CFA in the Wide overlap area is non-standard CFA, the overlap and non-overlap subsets of pixels may need different demosaicing processes. That is, the Wide overlap area may need a non-standard demosaicing process and the Wide non-overlap area may need a standard demosaicing process. Exemplary and non-limiting non-standard demosaicing interpolations for the overlap area of each of the Wide sensors shown in FIGS. **2-9** are given in detail below. The aim of the demosaicing is to reconstruct missing colors in each pixel. Demosaicing is applied also to the Tele sensor pixels if the Tele sensor is not a Clear only sensor. This will result in a Wide subset color image where the colors (in the overlap area) hold higher resolution than those of a standard CFA pattern. In step **1002**, the Tele image is registered (mapped) into the Wide image. The mapping includes finding correspondences between pixels in the two images. In step **1002**, actual registration is performed on luminance Tele and Wide images (respectively $Luma_{Tele}$ and $Luma_{wide}$) calculated from the pixel information of the Tele and Wide cameras. These luminance images are estimates for the scene luminance as captured by each camera and do not include any color information. If the Wide or Tele sensors have CFAs, the calculation of the luminance images is performed on the respective demosaiced images. The calculation of the Wide luminance image varies according to the type of non-standard CFA used in the Wide overlap area. If the CFA permits calculation of a full RGB demosaiced image, the luminance image calculation is straightforward. If the CFA is such that it does not permit calculation of a full RGB demosaiced image, the luminance image is estimated from the available color channels. If the Tele sensor is a Clear sensor, the Tele luminance image is just the pixel information. Performing the registration on luminance images has the advantage of enabling registration between images captured by sensors with different CFAs or between images captured by a standard CFA or non-standard CFA sensor and a standard CFA or Clear sensor and avoiding color artifacts that may arise from erroneous registration.

In step **1004**, the data from the Wide and Tele images is processed together with the registration information from step **1002** to form a high quality output zoom image. In cases where the Tele sensor is a Clear only sensor, the high resolution luminance component is taken from the Tele sensor and color resolution is taken from the Wide sensor. In cases where the Tele sensor includes a CFA, both color and luminance data are taken from the Tele subset to form the high quality zoom image. In addition, color and luminance data is taken from the Wide subset.

Exemplary Process for Fusing a Zoom Image

1. Special Demosaicing

In this step, the Wide image is interpolated to reconstruct the missing pixel values. Standard demosaicing is applied in the non-overlap area. If the overlap area includes a standard

CFA, standard demosaicing is applied there as well. If the overlap area includes a non-standard CFA, a special demosaicing algorithm is applied, depending on the CFA pattern used. In addition, in case the Tele sensor has a CFA, standard demosaicing is applied to reconstruct the missing pixel values in each pixel location and to generate a full RGB color image.

2. Registration Preparation

Tele image: a luminance image $Luma_{Tele}$ is calculated from the Tele sensor pixels. If the Tele subset has a Clear sensor, $_{LumaTele}$ is simply the sensor pixels data. If the Tele subset has a standard CFA, $_{LumaTele}$ is calculated from the demosaiced Tele image.

Wide image: as a first step, in case the Wide overlap CFA permits estimating the luminance component of the image, the luminance component is calculated from the demosaiced Wide image, $Luma_{Wide}$. If the CFA is one of those depicted in FIGS. **4-9**, a luminance image is calculated first. If the CFA is one of the CFAs depicted in FIG. **2** or FIG. **3**, a luminance image is not calculated. Instead, the following registration step is performed between a weighted average of the demosaiced channels of the Wide image and $Luma_{Tele}$. For convenience, this weighted average image is also denoted $Luma_{Wide}$. For example, if the Wide sensor CFA in the overlap region is as shown in FIG. **2**, the demosaiced channels R_{Wide} and B_{Wide} are averaged to create $Luma_{Wide}$ according to $Luma_{Wide}=(f1*R_{Wide}+f2*B_{Wide})/(f1+f2)$, where f**1** may be f**1**=**1** and f**2** may be f**2**=**1**.

Low-pass filtering is applied on the Tele luminance image in order to match its spatial frequency content to that of the $Luma_{Wide}$ image. This improves the registration performance, as after low-pass filtering the luminance images become more similar. The calculation is $Luma_{Tele}$→Low pass filter→$Luma_{Tele}^{LP}$, where "LP" denotes an image after low pass filtering.

3. Registration of $Luma_{Wide}$ and $Luma_{Tele}^{LP}$

This step of the algorithm calculates the mapping between the overlap areas in the two luminance images. The registration step does not depend on the type of CFA used (or the lack thereof), as it is applied on luminance images. The same registration step can therefore be applied on Wide and Tele images captured by standard CFA sensors, as well as by any combination of CFAs or Clear sensor pixels disclosed herein. The registration process chooses either the Wide image or the Tele image to be a primary image. The other image is defined as an auxiliary image. The registration process considers the primary image as the baseline image and registers the overlap area in the auxiliary image to it, by finding for each pixel in the overlap area of the primary image its corresponding pixel in the auxiliary image. The output image point of view is determined according to the primary image point of view (camera angle). Various correspondence metrics could be used for this purpose, among which are a sum of absolute differences and correlation.

In an embodiment, the choice of the Wide image or the Tele image as the primary and auxiliary images is based on the ZF chosen for the output image. If the chosen ZF is larger than the ratio between the focal-lengths of the Tele and Wide cameras, the Tele image is set to be the primary image and the Wide image is set to be the auxiliary image. If the chosen ZF is smaller than or equal to the ratio between the focal-lengths of the Tele and Wide cameras, the Wide image is set to be the primary image and the Tele image is set to be the auxiliary image. In another embodiment independent of a zoom factor, the Wide image is always the primary image and the Tele image is always the auxiliary image. The output of the registration stage is a map relating Wide image pixels indices to matching Tele image pixels indices.

4. Combination into a High Resolution Image

In this final step, the primary and auxiliary images are used to produce a high resolution image. One can distinguish between several cases:

a. If the Wide image is the primary image, and the Tele image was generated from a Clear sensor, $Luma_{Wide}$ is calculated and replaced or averaged with $Luma_{Tele}$ in the overlap area between the two images to create a luminance output image, matching corresponding pixels according to the registration map $Luma_{Out}=c1*Luma_{Wide}+c2*Luma_{Tele}$. The values of **c1** and **c2** may change between different pixels in the image. Then, RGB values of the output are calculated from $Luma_{Out}$ and R_{Wide}, G_{Wide}, and B_{Wide}.

b. If the Wide image is the primary image and the Tele image was generated from a CFA sensor, $Luma_{Tele}$ is calculated and is combined with $Luma_{Wide}$ in the overlap area between the two images, according to the flow described in 4a.

c. If the Tele image is the primary image generated from a Clear sensor, the RGB values of the output are calculated from the $Luma_{Tele}$ image and R_{Wide}, G_{Wide}, and B_{Wide} (matching pixels according to the registration map).

d. If the Tele image is the primary image generated from a CFA sensor, the RGB values of the output (matching pixels according to the registration map) are calculated either by using only the Tele image data, or by also combining data from the Wide image. The choice depends on the zoom factor.

Certain portions of the registered Wide and Tele images are used to generate the output image based on the ZF of the output image. In an embodiment, if the ZF of the output image defines a FOV smaller than the Tele FOV, the fused high resolution image is cropped to the required field of view and digital interpolation is applied to scale up the image to the required output image resolution.

Exemplary and Non-Limiting Pixel Interpolations Specifications for the Overlap Area

FIG. **2**

B11	B12	R13
R21	B22	B23
R31	R32	B33

In order to reconstruct the missing R**22** pixel, we perform R**22**=(R**31**+R**13**)/2. The same operation is performed for all missing Blue pixels.

FIG. **3**

R11	B12	R13
B21	R22	B23
R31	B32	R33

In order to reconstruct the missing B**22** pixel, we perform B**22**=(B**12**+B**21**+B**32**+B**23**)/4. The same operation is performed for all missing Red pixels.

FIG. **4**

Y11	C12	Y13
C21	Y22	C23
Y31	C32	Y33

In order to reconstruct the missing C22 pixel, we perform C22=(C12+C21+C32+C23)/4. The same operation is performed for all missing Yellow pixels.

FIG. 5

Case 1: W is Center Pixel

R11	B12	B13
R21	W22	R23
B31	B32	R33

In order to reconstruct the missing 22 pixels, we perform the following:

B22=(B12+B32)/2

R22=(R21+R23)/2

G22=(W22−R22−B22) (assuming that W includes the same amount of R, G and B colors).

Case 2: R22 is Center Pixel

B11	B12	R13	R14
W21	R22	B23	W24
B31	R32	B33	R34

B22=(B11+R33)/2

In order to reconstruct the missing 22 pixels, we perform the following:

W22=(2*W21+W24)/3

G22=(W22−R22−B22) (assuming that W contains the same amount of R, G and B colors). The same operation is performed for Blue as the center pixel.

FIG. 6

B11	B12	G13	R14
R21	G22	R23	B24
G31	B32	R33	G34
R41	R42	G43	B44

In order to reconstruct the missing 22 pixels, we perform the following:

B22=(B12+B32)/2

R22=(R21+R23)/2.

In order to reconstruct the missing 32 pixels, we perform the following:

G32=(2*G31+2*G22+G43)/5

R32=(R41+2*R42+2*R33+R23+R21)/7.

FIG. 7

G11	B12	R13	G14
R21	G22	B23	R24
B31	R32	G33	B34
G41	B42	R43	G44

In order to reconstruct the missing 22 pixels, we perform the following:

B22=(2*B12+2*B23+B31)/5

R22=(2*R21+2*R32+R13)/5

and similarly for all other missing pixels.

FIG. 8

R11	B12	B13	R14
R21	G22	R23	B24
B31	B32	R33	B34
R41	R42	B43	R44
B51	G52	B53	R54

In order to reconstruct the missing 22 pixels, we perform the following:

B22=(2*B12+2*B32+B13)/5

R22=(2*R21+2*R23+R11)/5.

In order to reconstruct the missing 32 pixels, we perform the following:

G32=(2*G22+G52)/3

R32=(2*R33+2*R42+R41+R21+R23)/7.

FIG. 9

R11	B12	R13	B14
B21	G22	B23	R24
R31	B32	R33	B34
B41	R42	B43	R44
R51	G52	R53	B54

In order to reconstruct the missing 22 pixels, we perform the following:

B22=(B12+B32+B23+B21)/4

R22=(R11+R13+R31+R33)/4.

In order to reconstruct the missing 32 pixels, we perform the following:

G32=(2*G22+G52)/3

R32=(R42+R31+R33)/3.

Triple-Aperture Zoom Imaging System with Improved Color Resolution

As mentioned, a multi-aperture zoom or non-zoom imaging system disclosed herein may include more than two apertures. A non-limiting and exemplary embodiment 1100 of a triple-aperture imaging system is shown in FIGS. 11A-11B. System 1100 includes a first Wide subset camera 1102 (with exemplarily X1), a second Wide subset camera (with exemplarily X1.5, and referred to as a "Wide-Tele" subset) and a Tele subset camera (with exemplarily X2). FIG. 11A shows exemplary images captured by imaging system 1100, while FIG. 11B illustrates schematically three sensors marked 1102, 1104 and 1106, which belong respectively to the Wide, Wide-Tele and Tele subsets. FIG. 11B also shows the CFA arrangements in each sensor: sensors 1102 and 1104 are similar to Wide sensors described above with reference to any of FIGS. 2-9, in the sense that they include an overlap area and a non-overlap area. The overlap area includes a non-standard CFA. In both Wide sensors, the non-overlap area may have a Clear pattern or a standard CFA. Thus, neither Wide subset is solely a Clear channel camera. The Tele sensor may be Clear or have a standard Bayer CFA or a standard non-Bayer CFA. In use, an image is acquired with imaging system 1100 and processed as follows: demosaicing is performed on the overlap area pixels of the Wide and Wide-Tele sensors according to the specific CFA pattern in each overlap area. The overlap and non-overlap subsets of pixels in each of these sensors may need different demos aicing. Exemplary and non-limiting demosaicing specifications for the overlap area for Wide sensors shown in FIGS. 2-9 are given above. The aim is to reconstruct the missing colors in each and every pixel. In cases in which the Tele subset sensor is not Clear only, demosaicing is performed as well. The Wide and Wide-Tele subset color images acquired this way will have colors (in the overlap area) holding higher resolution than that of a standard CFA pattern. Then, the Tele image acquired with the Tele sensor is registered (mapped) into the respective Wide image. The data from the Wide, Wide-Tele and Tele images is then processed to form a high quality zoom image. In cases where the Tele subset is Clear only, high Luma resolution is taken from the Tele sensor and color resolution is taken from the Wide sensor. In cases where the Tele subset includes a CFA, both color and Luma resolution is taken from the Tele subset. In addition, color resolution is taken from the Wide sensor. The resolution of the fused image may be higher than the resolution of both sensors.

While this disclosure has been described in terms of certain embodiments and generally associated methods, alterations and permutations of the embodiments and methods will be apparent to those skilled in the art. For example, multi-aperture imaging systems with more than two Wide or Wide-Tele subsets (and sensors) or with more than one Tele subset (and sensor) may be constructed and used according to principles set forth herein. Similarly, non-zoom multi-aperture imaging systems with more than two sensors, at least one of which has a non-standard CFA, may be constructed and used according to principles set forth herein. The disclosure is to be understood as not limited by the specific embodiments described herein, but only by the scope of the appended claims.

What is claimed is:

[1. A multi-aperture imaging system comprising:

a) a first camera that provides a first camera image, the first camera having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard color filter array (CFA) used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA, wherein the non-standard CFA includes a repetition of a n×n micro-cell where n=4 and wherein each micro-cell includes a BBRR-RBBR-RRBB-BRRB color filter order;

b) a second camera that provides a second camera image, the second camera having a second sensor with a second plurality of sensor pixels, the second plurality of sensor pixels being either Clear or covered with a standard CFA, wherein the second camera image has an overlap area with the first camera image; and

c) a processor configured to process the first and second camera images into a fused output image, wherein in the overlap area pixels of the second camera image are registered with corresponding pixels of the first camera image.]

[2. A multi-aperture imaging system comprising:

a) a first camera that provides a first camera image, the first camera having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard color filter array (CFA) used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA, wherein the non-standard CFA includes a repetition of a n×n micro-cell where n=6 and wherein each micro-cell includes a color filter order selected from the group consisting of RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, BBGRRG-RGRBGB-GBR-GRB-RRGBBG-BGBRGR-GRBGBR, RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR and RBRBRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR;

b) a second camera that provides a second camera image, the second camera having a second sensor with a second plurality of sensor pixels, the second plurality of sensor pixels being either Clear or covered with a standard CFA, wherein the second camera image has an overlap area with the first camera image; and

c) a processor configured to process the first and second camera images into a fused output image, wherein in the overlap area pixels of the second camera image are registered with corresponding pixels of the first camera image.]

[3. The multi-aperture imaging system of claim 1, wherein the first camera is a Wide camera with a field of view FOV_w and wherein the second camera is a Tele camera with a field of view FOV_T smaller than FOV_w.]

[4. A method of acquiring images by a multi-aperture imaging system, the method comprising:

a) providing a first image generated by a first camera of the imaging system, the first camera having a first field of view (FOV_1);

b) providing a second image generated by a second camera of the imaging system, the second camera having a second field of view (FOV_2) such that $FOV_2<FOV_1$, the second image having an overlap area with the first image; and

c) fusing the first and second images into a fused image, wherein the fusing includes applying a registration process between the first and second images, the registration process including:

i. extracting a first Luma image from the first image

ii. extracting a second Luma image from the second image,

iii. applying low-pass filtering on the second Luma image in order to match its spatial frequency content to that of the first Luma image and to generate a low-pass second Luma image, and

iv. applying registration on the low-pass second Luma image and the first Luma image,

wherein the non-standard CFA includes a repetition of a n×n micro-cell where n=4 and

wherein each micro-cell includes a BBRR-RBBR-RRBB-BRRB color filter order.]

[5. The method of claim 4, wherein n=6 instead of n=4 and wherein instead of each micro-cell including a BBRR-RBBR-RRBB-BRRB color filter order, each micro-cell includes a color filter order selected from the group consisting of RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR, RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR and RBRBRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR.]

6. A multi-aperture imaging system, comprising:

a) a first camera that provides a first image, the first camera having a fixed first field of view (FOV1) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);

b) a second camera that provides a second image, the second camera having a fixed second field of view (FOV2) such that FOV2<FOV1 and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area; and

c) a third camera that provides a third image, the third camera having a fixed third field of view (FOV3) such that FOV3<FOV2, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and

d) a processor configured to provide an output image based on a zoom factor (ZF) input that defines a respective field of view (FOVZF), such that for FOV2<FOVZF<FOV1 the processor is further configured to select the first image as a primary image, to register the overlap area of the second image to the first

image to obtain a fused image, and to provide the fused image as the output image from the point of view of the first camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

7. The multi-aperture imaging system of claim 6, wherein if FOV3>FOVZF, then the processor is further configured to provide an output image from the point of view of the third camera.

8. A multi-aperture imaging system, comprising:

a) a first camera that provides a first image, the first camera having a fixed first field of view (FOV1) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);

b) a second camera that provides a second image, the second camera having a fixed second field of view (FOV2) such that FOV2 < FOV1 and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area; and

c) a third camera that provides a third image, the third camera having a fixed third field of view (FOV3) such that FOV3 < FOV2, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and

d) a processor configured to provide an output image based on a zoom factor (ZF) input that defines a respective field of view (FOVZF), such that for FOV3 < FOVZF < FOV2 the processor is further configured to select the second image as a primary image, to register the overlap area of the third image to the second image to obtain a fused image, and to provide the fused image as the output image from the point of view of the second camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

9. The multi-aperture imaging system of claim 8, wherein if FOV3>FOVZF, then the processor is further configured to provide the output image from the point of view of the third camera.

10. A method of acquiring images by a multi-aperture imaging system, comprising:

a) providing a first image generated by a first camera of the imaging system, the first camera having a fixed first field of view (FOV1) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);

b) providing a second image generated by a second camera of the imaging system, the second camera having a fixed second field of view (FOV2) such that FOV2 < FOV1, and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area;

c) providing a third image generated by a third camera of the imaging system, the third camera having a fixed third field of view (FOV3) such that FOV3 < FOV2, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and

d) using a processor to provide an output image from a point of view of the first camera, the second camera, or the third camera, based on a zoom factor (ZF) input that defines a respective field of view (FOVZF) such that:

if FOV2 < FOVZF < FOV1, then the processor is configured to select the first image as a primary image, to register the overlap area of the second image to the first image to obtain a fused image and to provide the fused image as the output image from the point of view of the first camera,

if FOV3 < FOVZF < FOV2, then the processor is configured to select the second image as a primary image, to register the overlap area of the third image to the second image to obtain a fused image and to provide the fused image as the output image from the point of view of the second camera, and

if FOV3>FOVZF, then the processor is configured to provide an output image from the point of view of the third camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

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