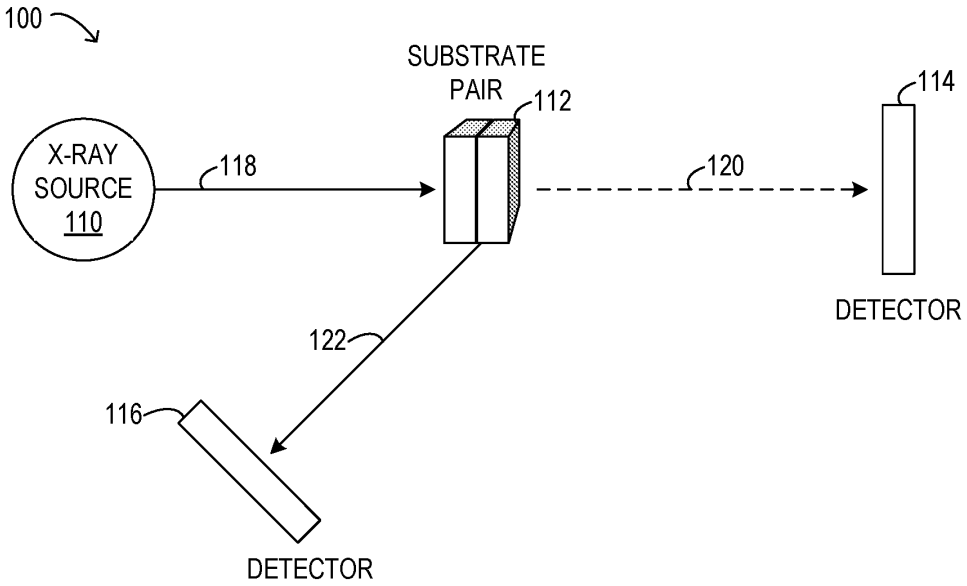

100
SUBSTRATE
PAIR
112
114
X-RAY
SOURCE
110
118
120
DETECTOR
122
116
DETECTOR

FIG. 1

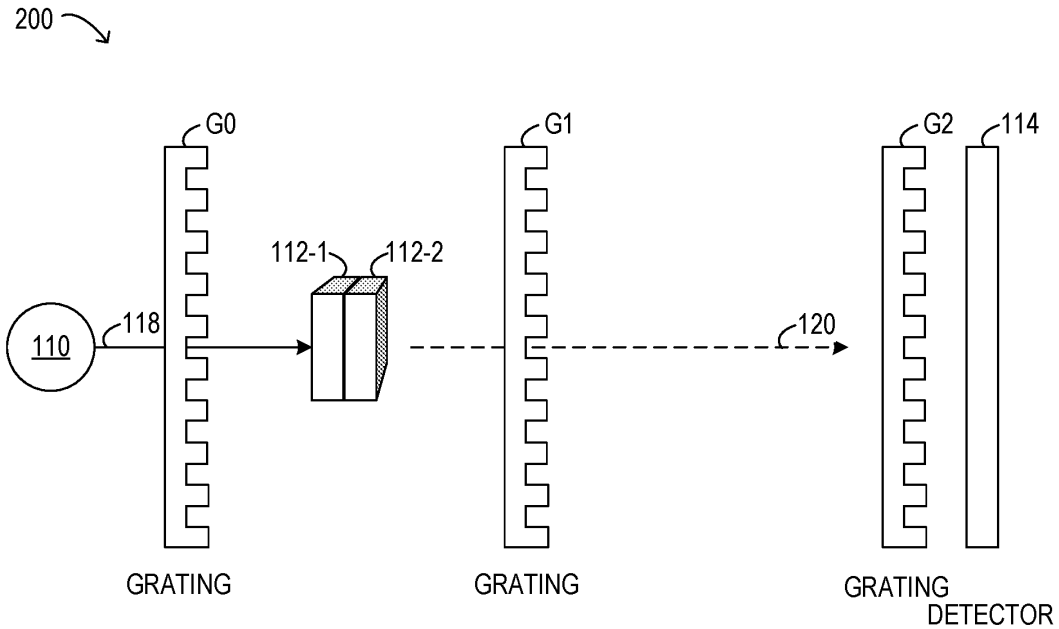

200
G0
G1
G2
114
112-1
112-2
110
118
120
GRATING
GRATING
GRATING
DETECTOR

FIG. 2

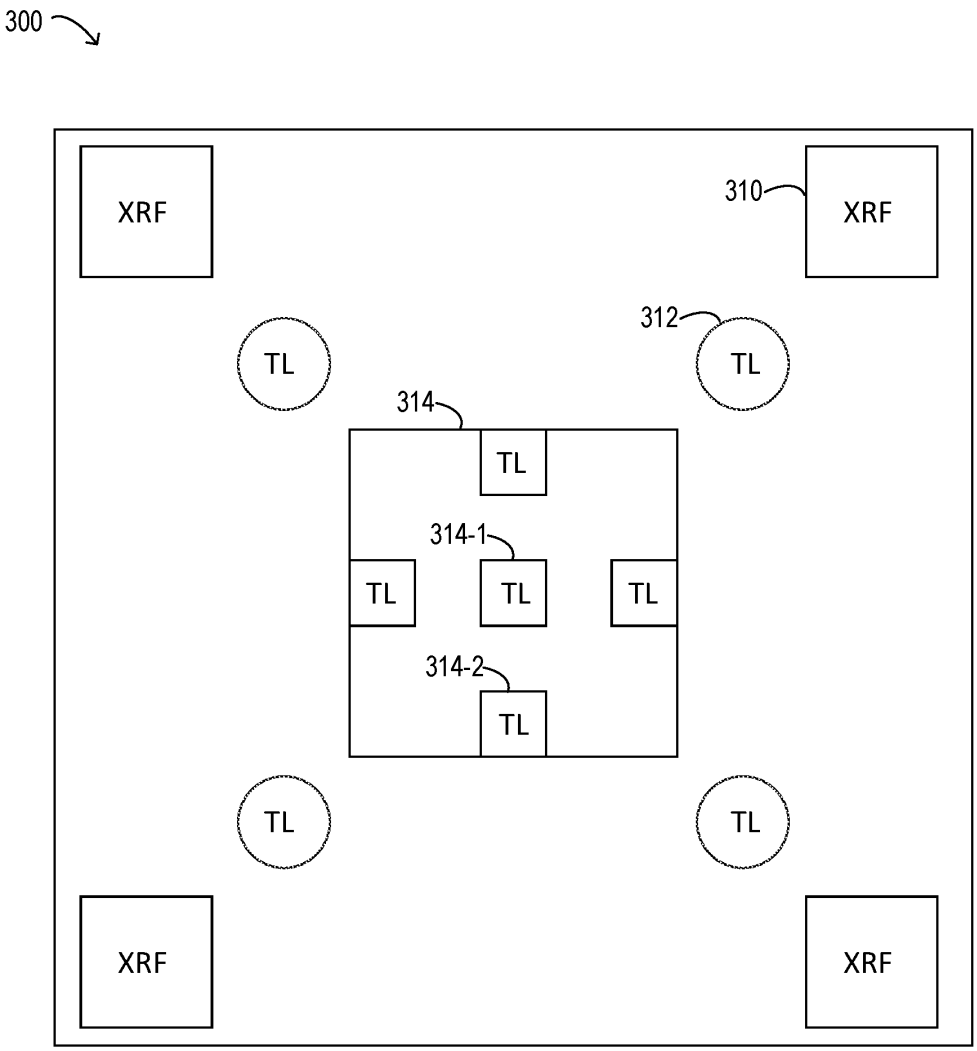

300
XRF
310
XRF
312
TL
TL
314
TL
314-1
TL
TL
TL
314-2
TL
TL
TL
XRF
XRF
X
302
Z
Y

FIG. 3

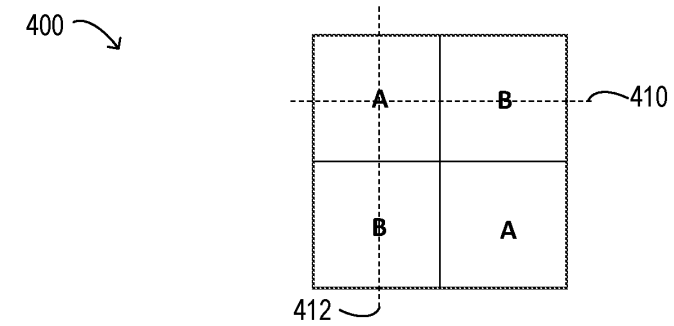


FIG. 4A

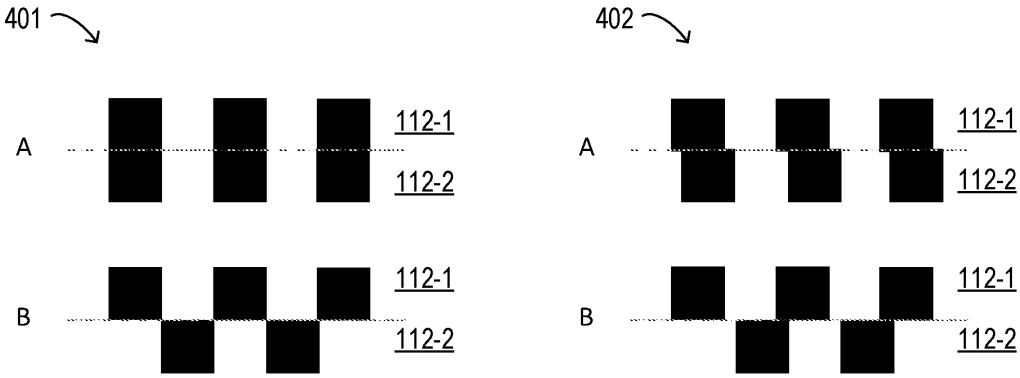


FIG. 4B

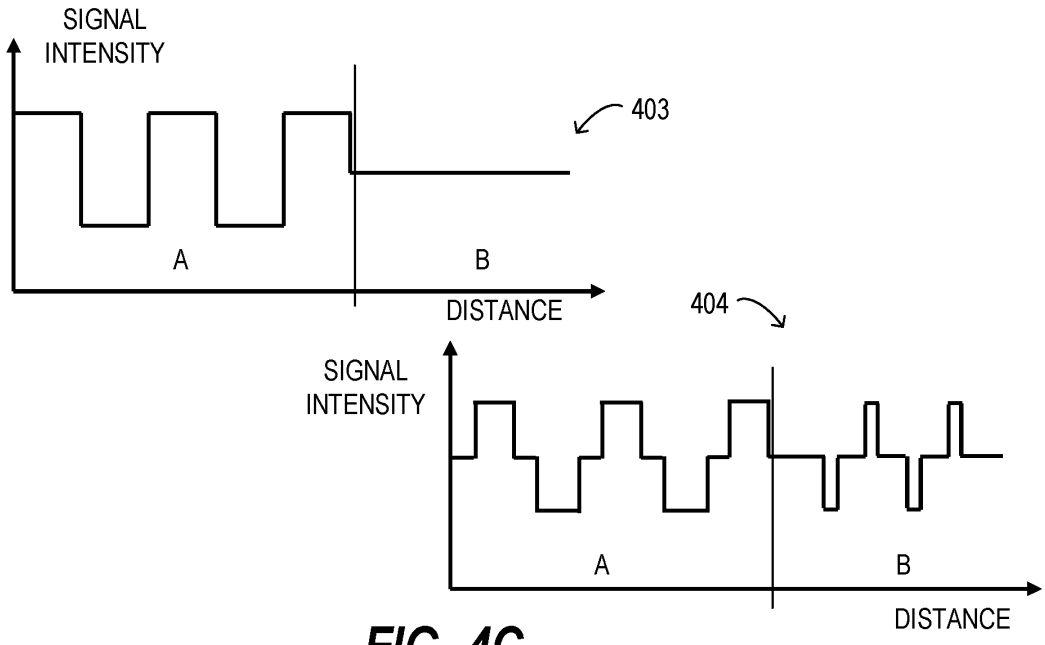


FIG. 4C

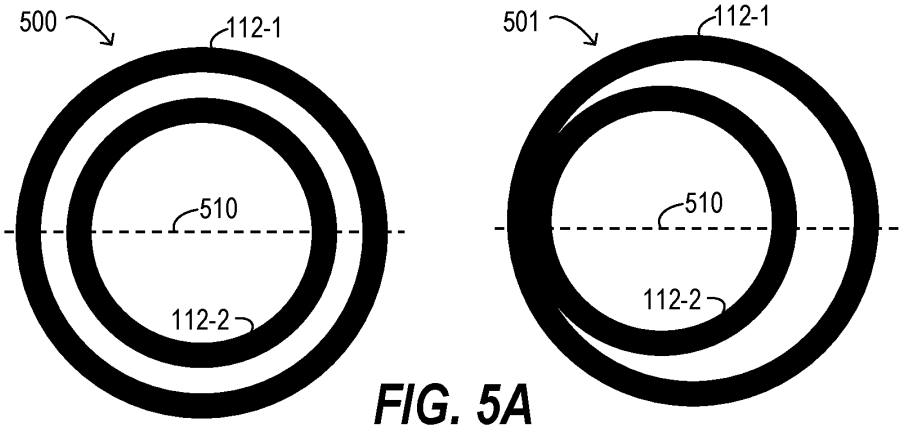


FIG. 5A

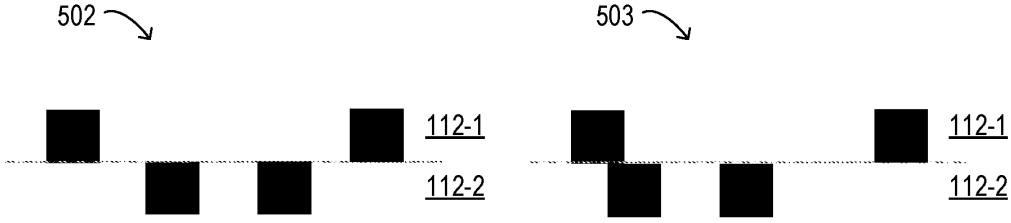


FIG. 5B

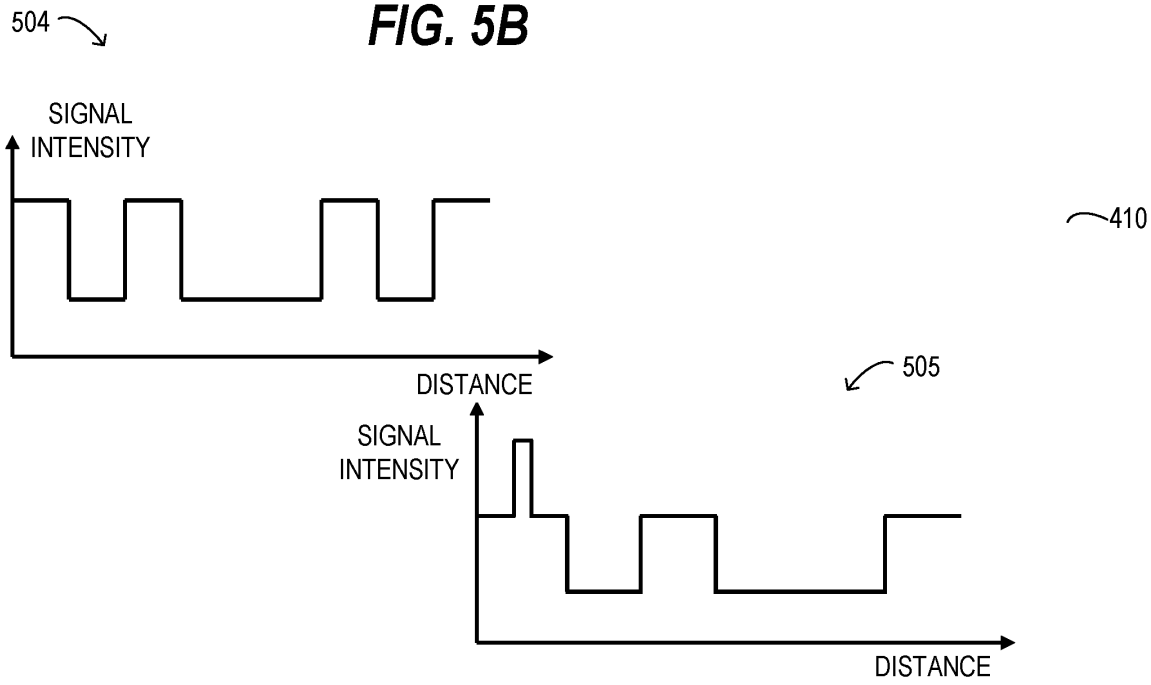


FIG. 5C

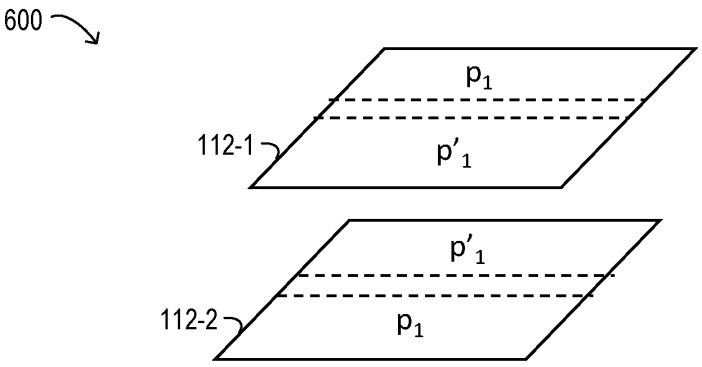


FIG. 6A

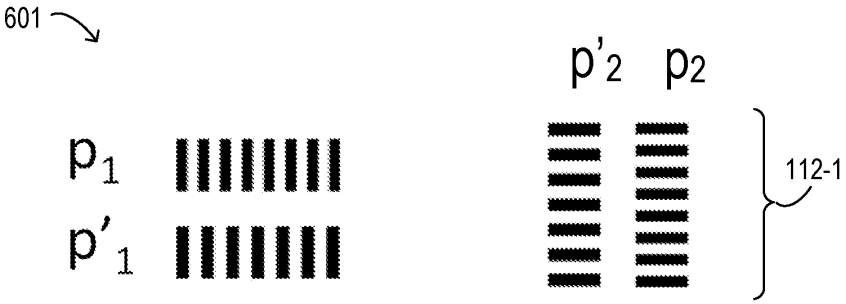


FIG. 6B

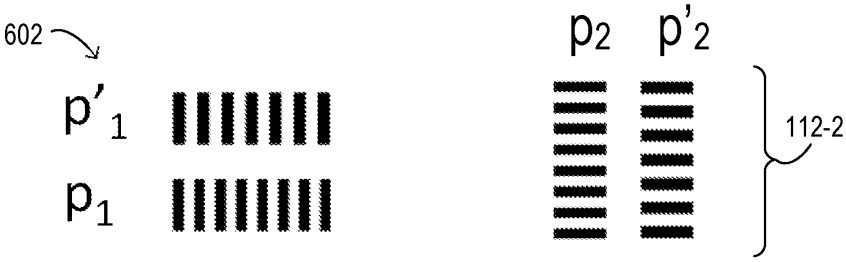


FIG. 6C

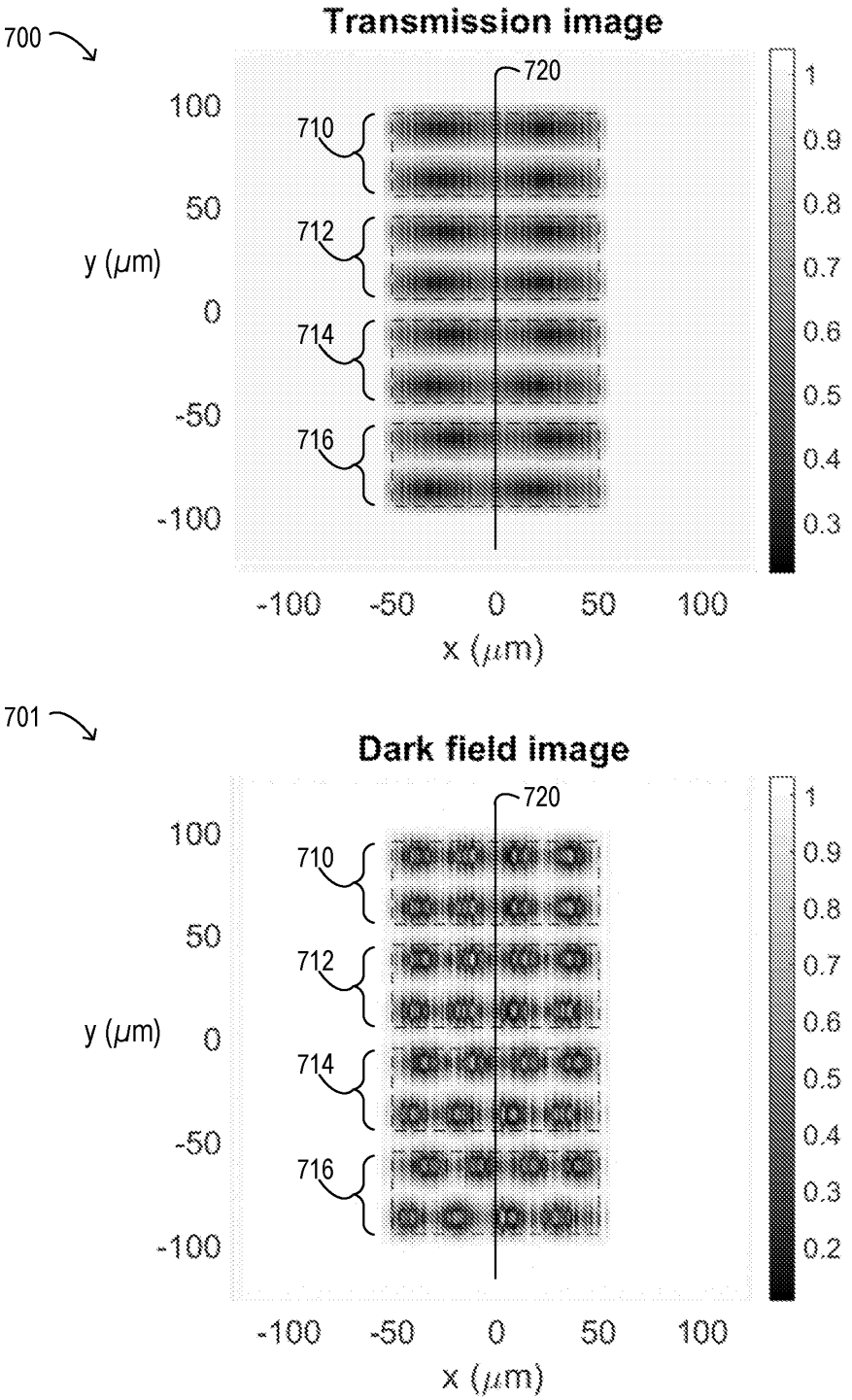

700
Transmission image
720
710
712
714
716
100
50
0
-50
-100
y (μm)
-100 -50 0 50 100
x (μm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
701
Dark field image
720
710
712
714
716
100
50
0
-50
-100
y (μm)
-100 -50 0 50 100
x (μm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

FIG. 7A

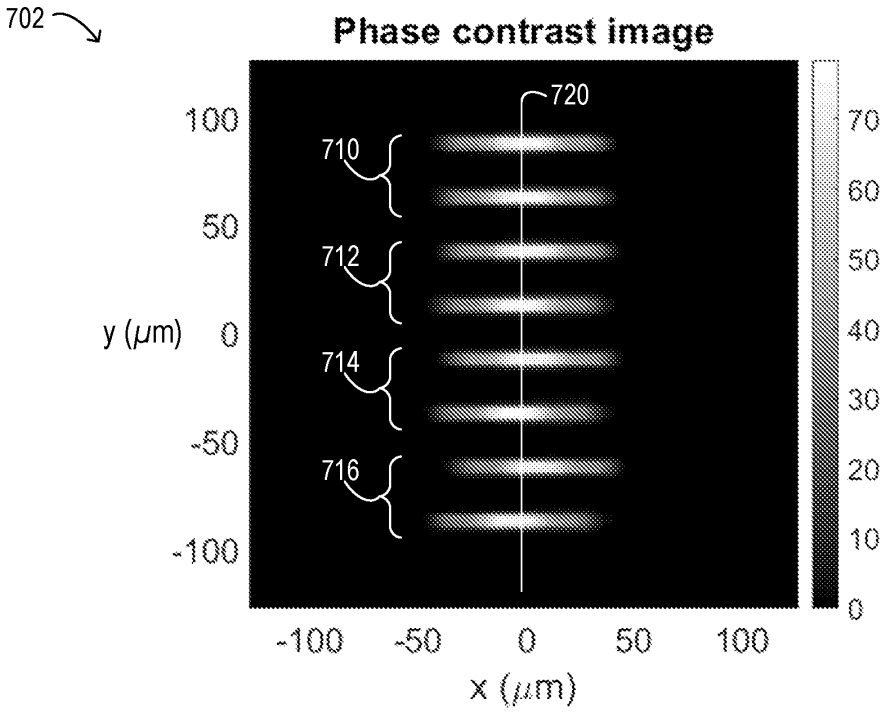

702
Phase contrast image
720
710
712
714
716
100
50
0
-50
-100
y (μm)
-100
-50
0
50
100
x (μm)
70
60
50
40
30
20
10
0

FIG. 7B

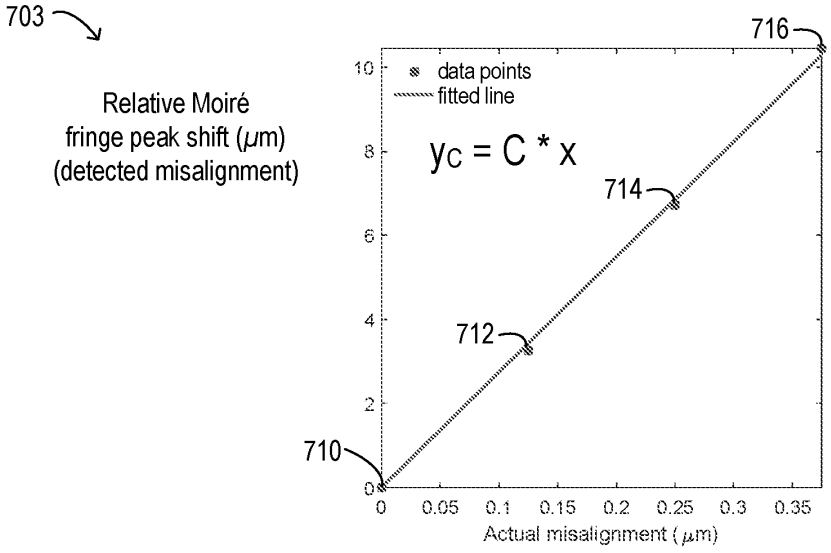

703
Relative Moiré
fringe peak shift (μm)
(detected misalignment)
716
data points
fitted line
yc = C * x
714
712
710
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Actual misalignment (μm)

FIG. 7C

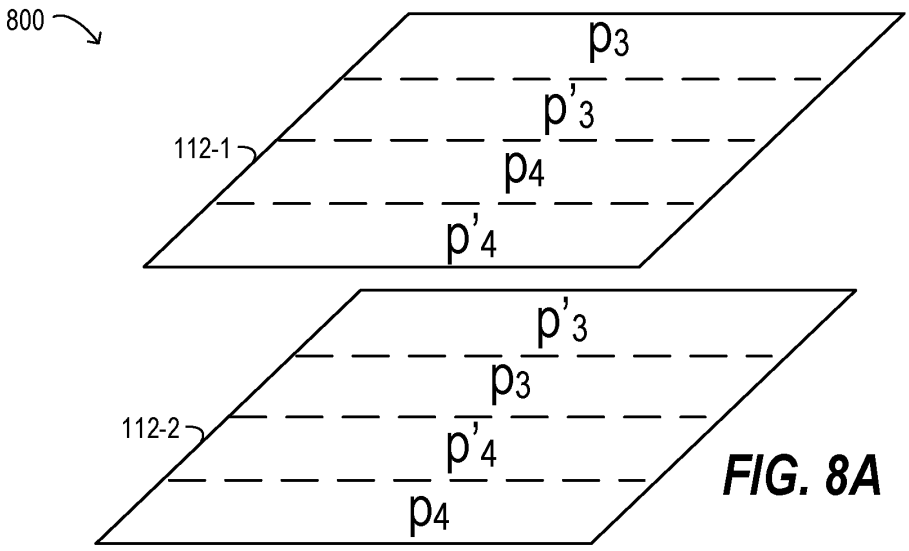


FIG. 8A

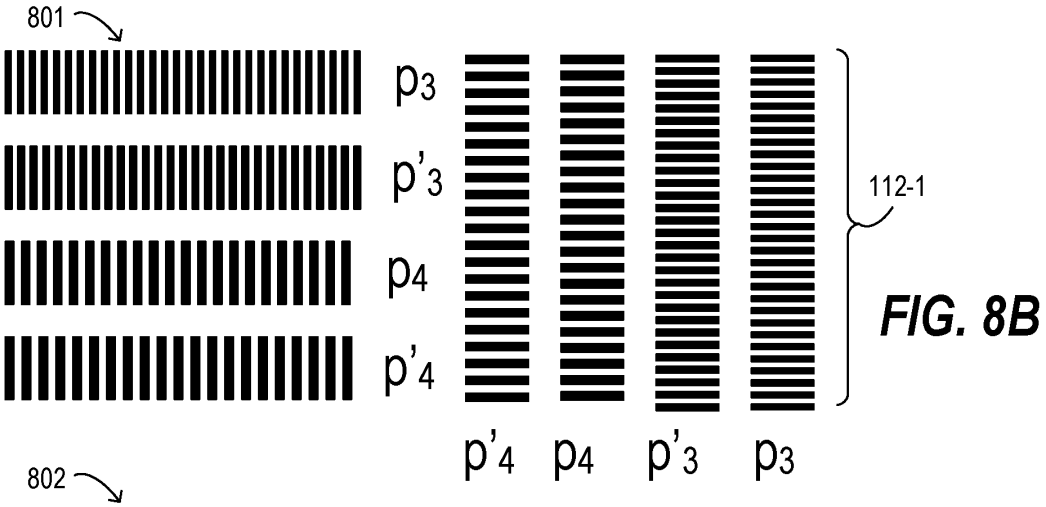


FIG. 8B

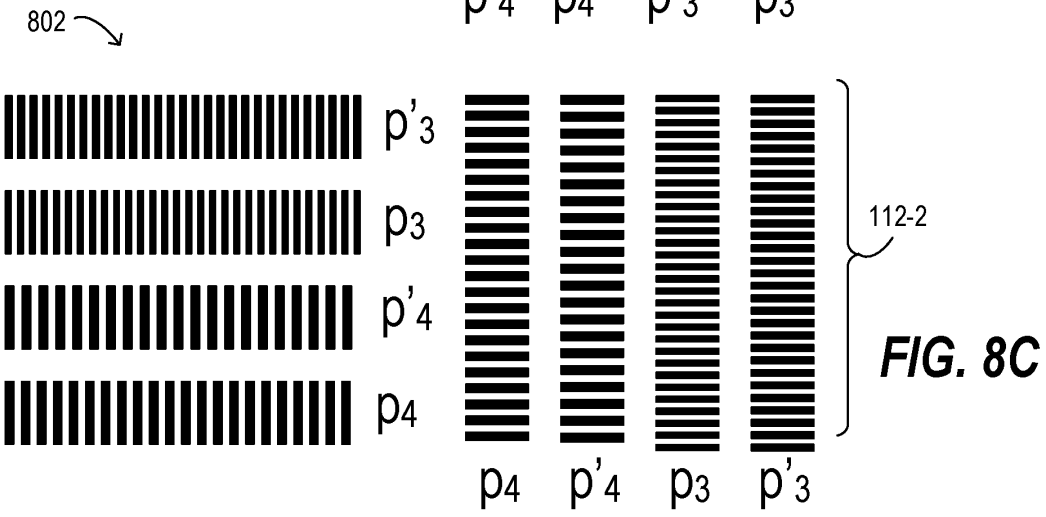


FIG. 8C

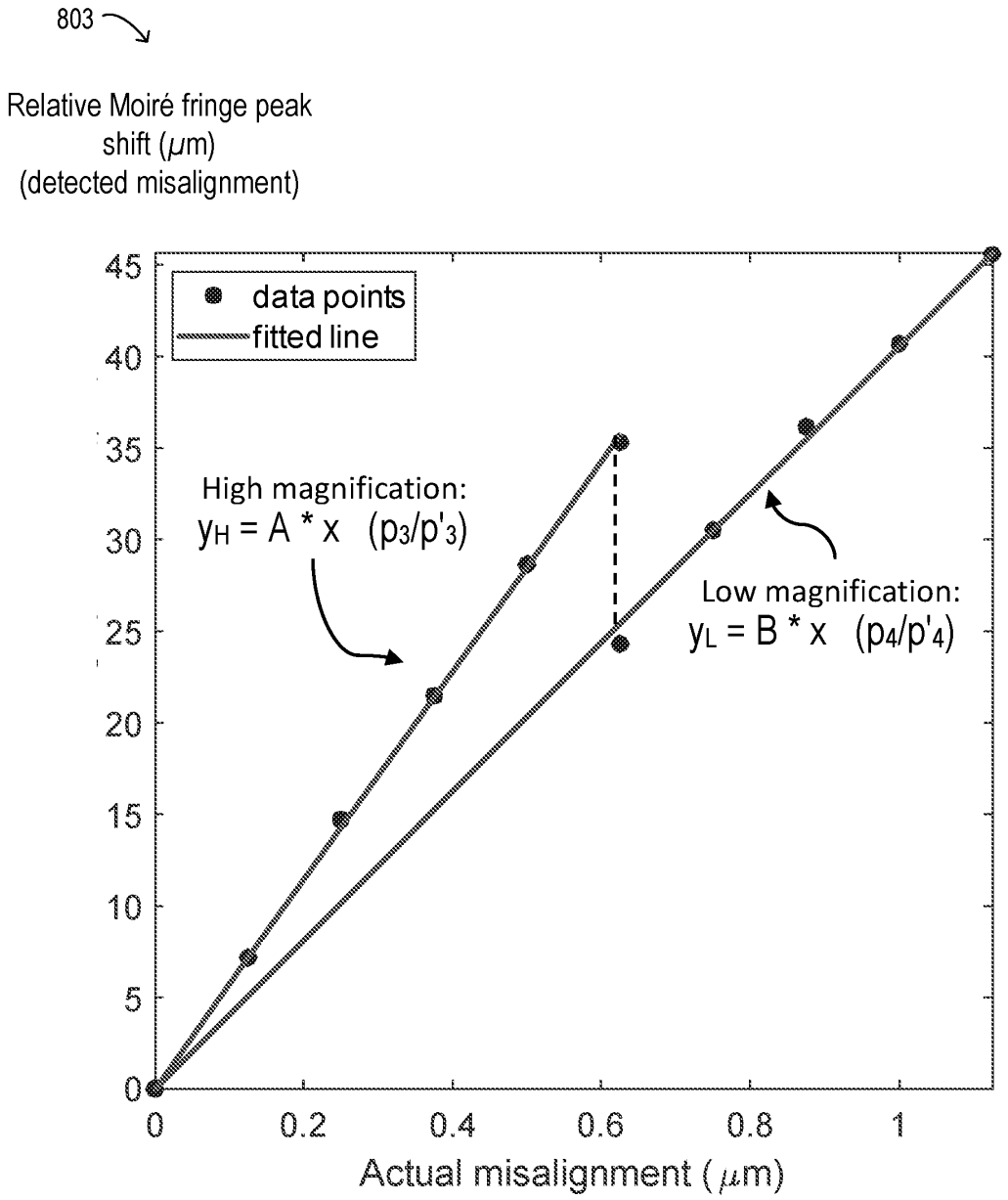

803
Relative Moiré fringe peak shift (μm) (detected misalignment)
data points
fitted line
High magnification:
$y_H = A * x \quad (p_3/p'_3)$
Low magnification:
$y_L = B * x \quad (p_4/p'_4)$
45
40
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
Actual misalignment (μm)

FIG. 8D

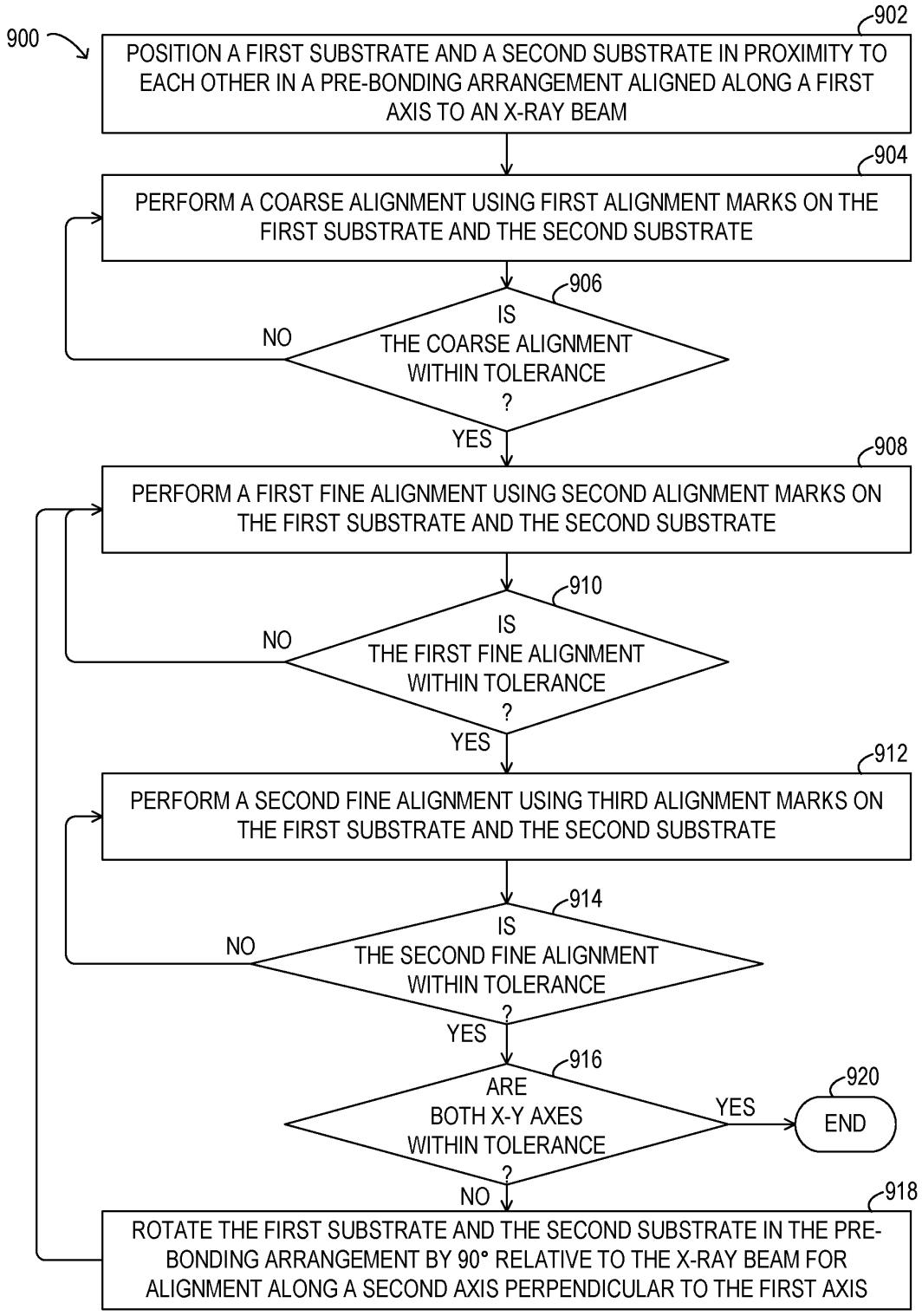

900
902
POSITION A FIRST SUBSTRATE AND A SECOND SUBSTRATE IN PROXIMITY TO EACH OTHER IN A PRE-BONDING ARRANGEMENT ALIGNED ALONG A FIRST AXIS TO AN X-RAY BEAM
904
PERFORM A COARSE ALIGNMENT USING FIRST ALIGNMENT MARKS ON THE FIRST SUBSTRATE AND THE SECOND SUBSTRATE
906
IS THE COARSE ALIGNMENT WITHIN TOLERANCE ?
NO
YES
908
PERFORM A FIRST FINE ALIGNMENT USING SECOND ALIGNMENT MARKS ON THE FIRST SUBSTRATE AND THE SECOND SUBSTRATE
910
IS THE FIRST FINE ALIGNMENT WITHIN TOLERANCE ?
NO
YES
912
PERFORM A SECOND FINE ALIGNMENT USING THIRD ALIGNMENT MARKS ON THE FIRST SUBSTRATE AND THE SECOND SUBSTRATE
914
IS THE SECOND FINE ALIGNMENT WITHIN TOLERANCE ?
NO
YES
916
ARE BOTH X-Y AXES WITHIN TOLERANCE ?
YES
920
END
NO
918
ROTATE THE FIRST SUBSTRATE AND THE SECOND SUBSTRATE IN THE PRE-BONDING ARRANGEMENT BY 90° RELATIVE TO THE X-RAY BEAM FOR ALIGNMENT ALONG A SECOND AXIS PERPENDICULAR TO THE FIRST AXIS

FIG. 9

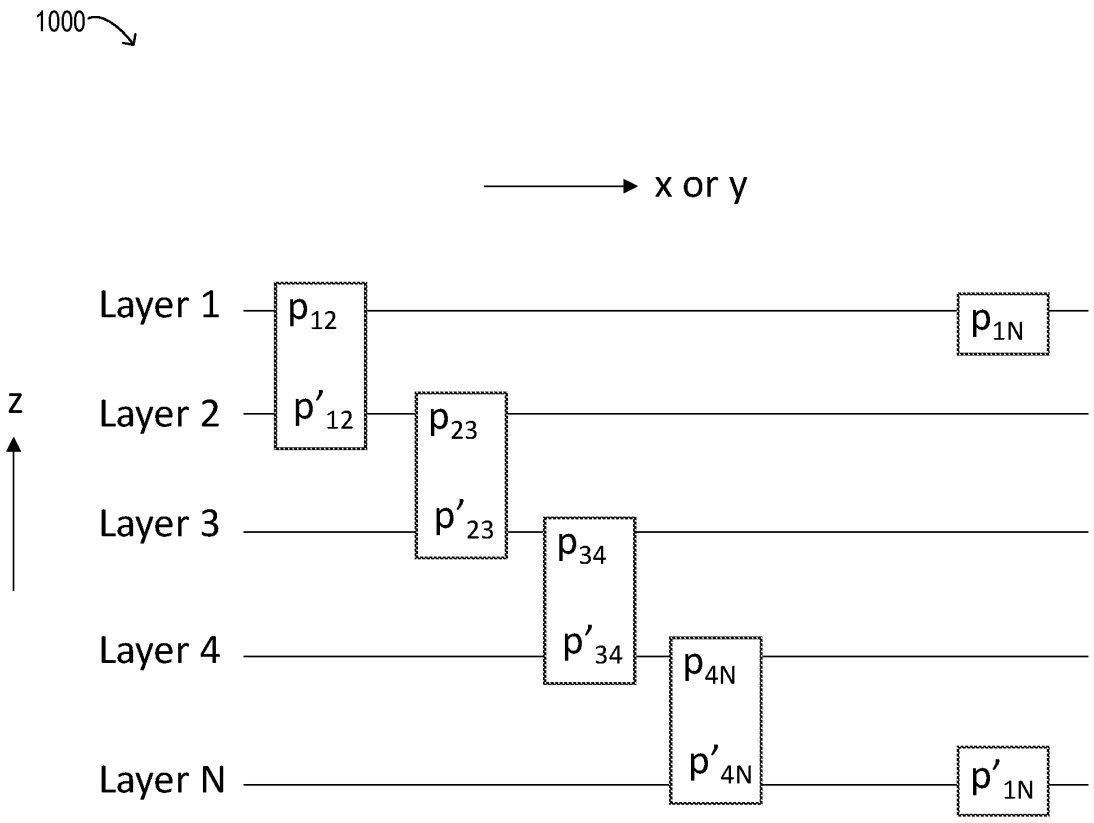

1000
x or y
z
Layer 1
Layer 2
Layer 3
Layer 4
Layer N
p_{12}
p'_{12}
p_{23}
p'_{23}
p_{34}
p'_{34}
p_{4N}
p'_{4N}
p_{1N}
p'_{1N}

FIG. 10A

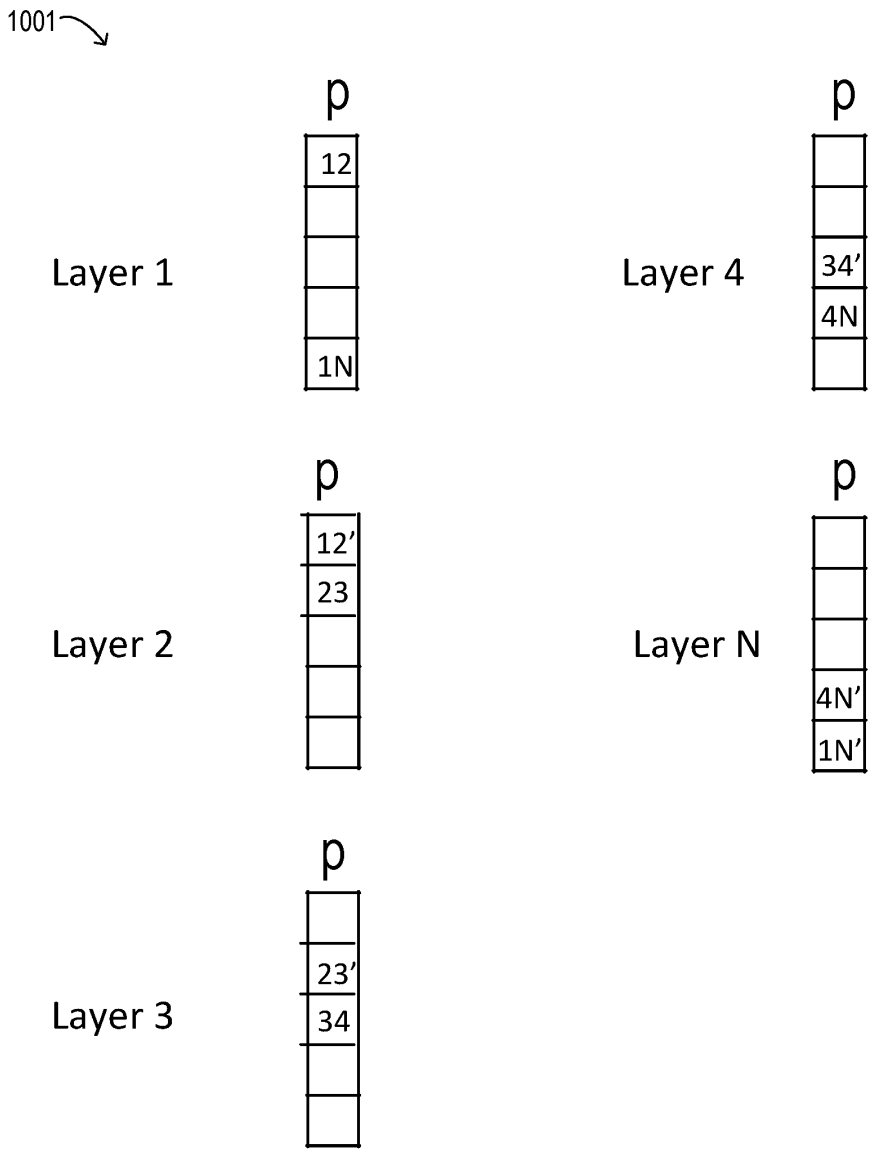

1001
p
12
1N
Layer 1
p
34’
4N
Layer 4
p
12’
23
Layer 2
p
4N’
1N’
Layer N
p
23’
34
Layer 3

FIG. 10B

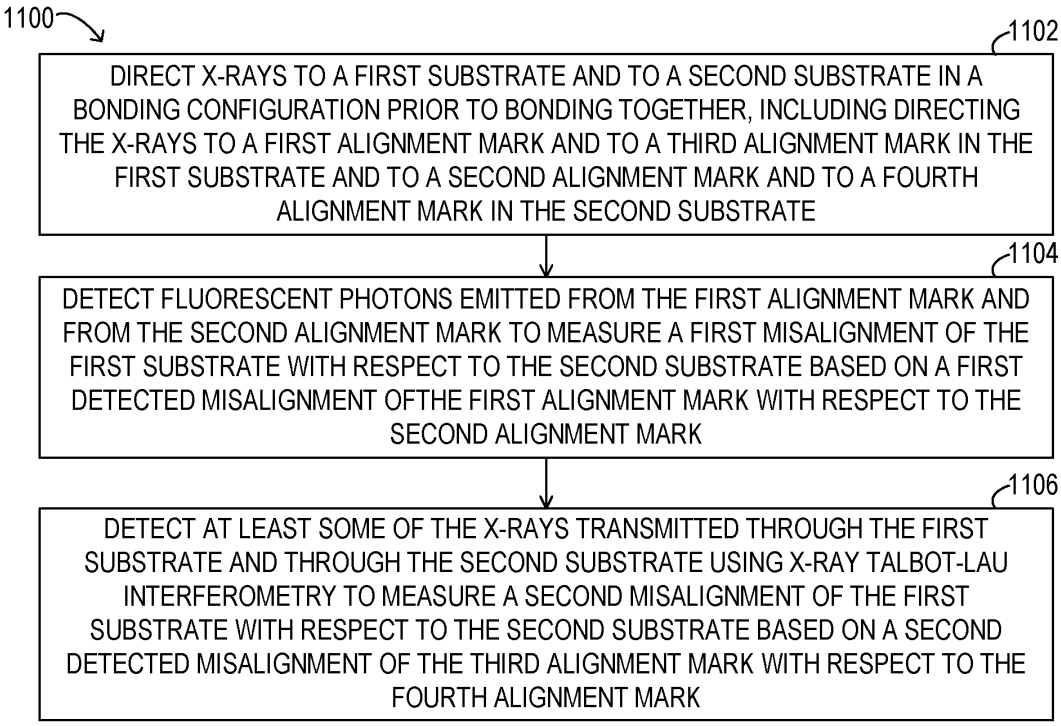

1100
1102
DIRECT X-RAYS TO A FIRST SUBSTRATE AND TO A SECOND SUBSTRATE IN A BONDING CONFIGURATION PRIOR TO BONDING TOGETHER, INCLUDING DIRECTING THE X-RAYS TO A FIRST ALIGNMENT MARK AND TO A THIRD ALIGNMENT MARK IN THE FIRST SUBSTRATE AND TO A SECOND ALIGNMENT MARK AND TO A FOURTH ALIGNMENT MARK IN THE SECOND SUBSTRATE
1104
DETECT FLUORESCENT PHOTONS EMITTED FROM THE FIRST ALIGNMENT MARK AND FROM THE SECOND ALIGNMENT MARK TO MEASURE A FIRST MISALIGNMENT OF THE FIRST SUBSTRATE WITH RESPECT TO THE SECOND SUBSTRATE BASED ON A FIRST DETECTED MISALIGNMENT OFTHE FIRST ALIGNMENT MARK WITH RESPECT TO THE SECOND ALIGNMENT MARK
1106
DETECT AT LEAST SOME OF THE X-RAYS TRANSMITTED THROUGH THE FIRST SUBSTRATE AND THROUGH THE SECOND SUBSTRATE USING X-RAY TALBOT-LAU INTERFEROMETRY TO MEASURE A SECOND MISALIGNMENT OF THE FIRST SUBSTRATE WITH RESPECT TO THE SECOND SUBSTRATE BASED ON A SECOND DETECTED MISALIGNMENT OF THE THIRD ALIGNMENT MARK WITH RESPECT TO THE FOURTH ALIGNMENT MARK

FIG. 11

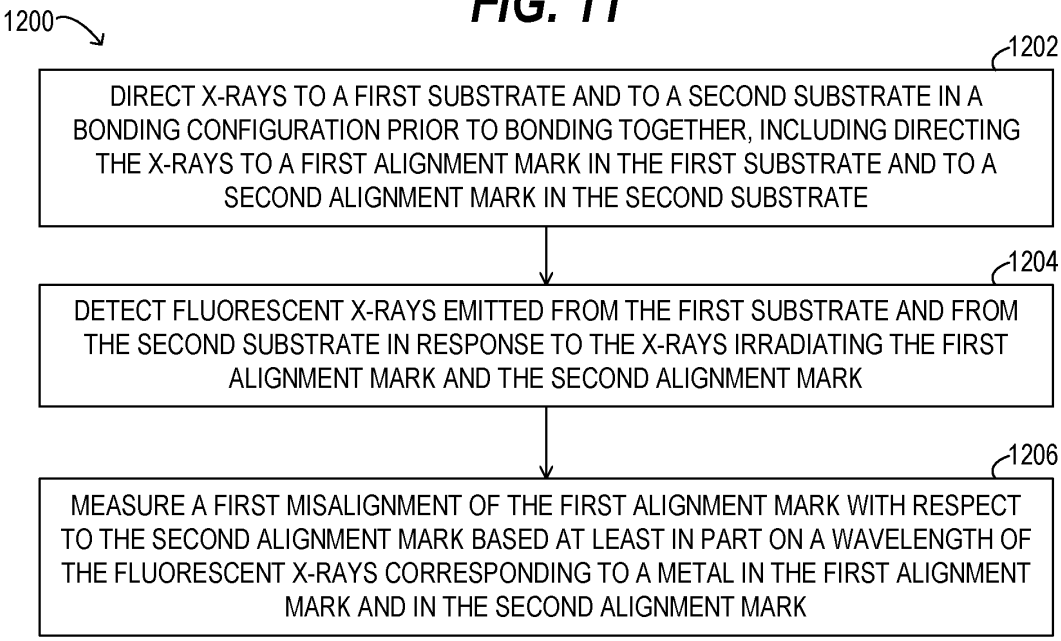

1200
1202
DIRECT X-RAYS TO A FIRST SUBSTRATE AND TO A SECOND SUBSTRATE IN A BONDING CONFIGURATION PRIOR TO BONDING TOGETHER, INCLUDING DIRECTING THE X-RAYS TO A FIRST ALIGNMENT MARK IN THE FIRST SUBSTRATE AND TO A SECOND ALIGNMENT MARK IN THE SECOND SUBSTRATE
1204
DETECT FLUORESCENT X-RAYS EMITTED FROM THE FIRST SUBSTRATE AND FROM THE SECOND SUBSTRATE IN RESPONSE TO THE X-RAYS IRRADIATING THE FIRST ALIGNMENT MARK AND THE SECOND ALIGNMENT MARK
1206
MEASURE A FIRST MISALIGNMENT OF THE FIRST ALIGNMENT MARK WITH RESPECT TO THE SECOND ALIGNMENT MARK BASED AT LEAST IN PART ON A WAVELENGTH OF THE FLUORESCENT X-RAYS CORRESPONDING TO A METAL IN THE FIRST ALIGNMENT MARK AND IN THE SECOND ALIGNMENT MARK

FIG. 12

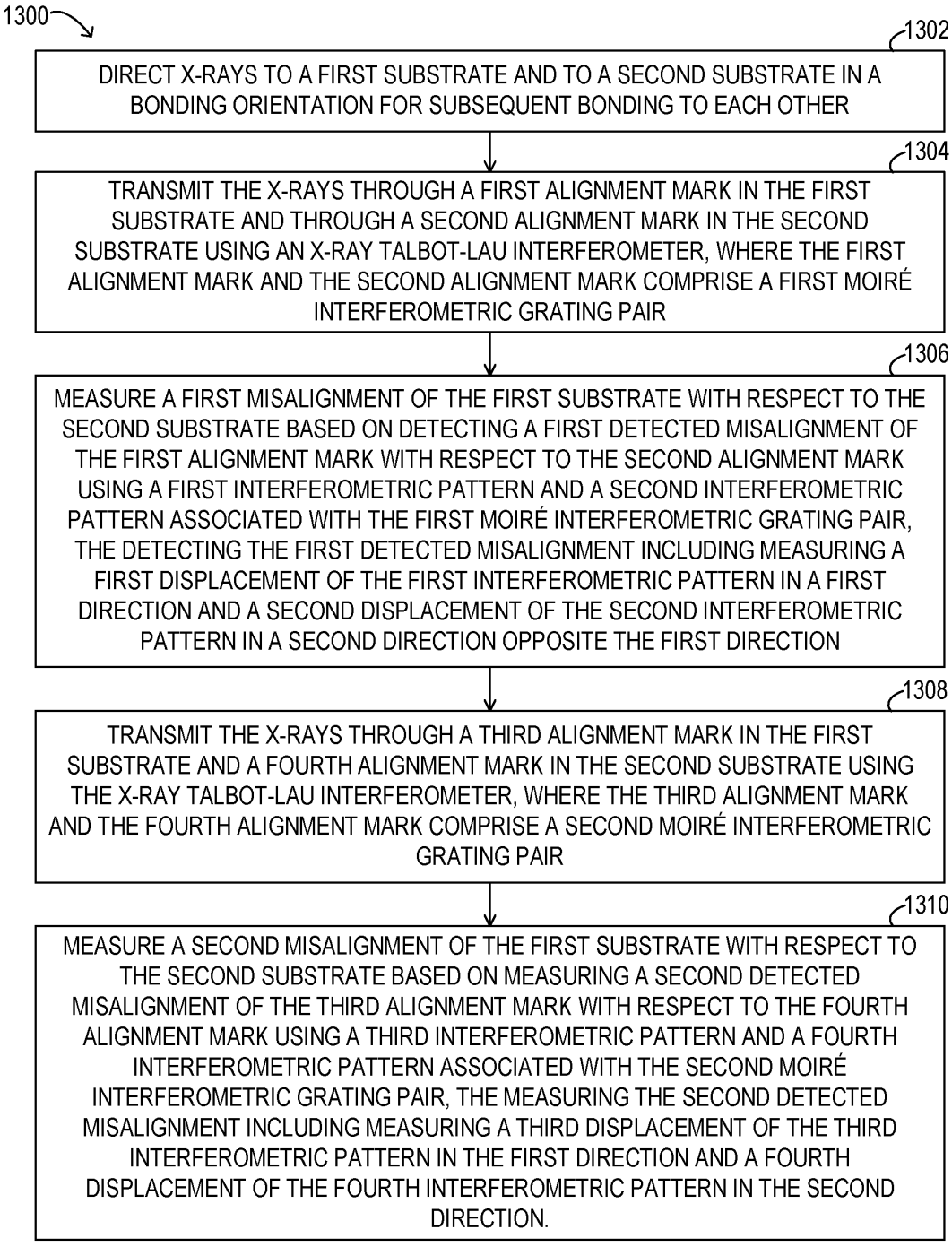

1300
1302
DIRECT X-RAYS TO A FIRST SUBSTRATE AND TO A SECOND SUBSTRATE IN A BONDING ORIENTATION FOR SUBSEQUENT BONDING TO EACH OTHER
1304
TRANSMIT THE X-RAYS THROUGH A FIRST ALIGNMENT MARK IN THE FIRST SUBSTRATE AND THROUGH A SECOND ALIGNMENT MARK IN THE SECOND SUBSTRATE USING AN X-RAY TALBOT-LAU INTERFEROMETER, WHERE THE FIRST ALIGNMENT MARK AND THE SECOND ALIGNMENT MARK COMPRISE A FIRST MOIRÉ INTERFEROMETRIC GRATING PAIR
1306
MEASURE A FIRST MISALIGNMENT OF THE FIRST SUBSTRATE WITH RESPECT TO THE SECOND SUBSTRATE BASED ON DETECTING A FIRST DETECTED MISALIGNMENT OF THE FIRST ALIGNMENT MARK WITH RESPECT TO THE SECOND ALIGNMENT MARK USING A FIRST INTERFEROMETRIC PATTERN AND A SECOND INTERFEROMETRIC PATTERN ASSOCIATED WITH THE FIRST MOIRÉ INTERFEROMETRIC GRATING PAIR, THE DETECTING THE FIRST DETECTED MISALIGNMENT INCLUDING MEASURING A FIRST DISPLACEMENT OF THE FIRST INTERFEROMETRIC PATTERN IN A FIRST DIRECTION AND A SECOND DISPLACEMENT OF THE SECOND INTERFEROMETRIC PATTERN IN A SECOND DIRECTION OPPOSITE THE FIRST DIRECTION
1308
TRANSMIT THE X-RAYS THROUGH A THIRD ALIGNMENT MARK IN THE FIRST SUBSTRATE AND A FOURTH ALIGNMENT MARK IN THE SECOND SUBSTRATE USING THE X-RAY TALBOT-LAU INTERFEROMETER, WHERE THE THIRD ALIGNMENT MARK AND THE FOURTH ALIGNMENT MARK COMPRISE A SECOND MOIRÉ INTERFEROMETRIC GRATING PAIR
1310
MEASURE A SECOND MISALIGNMENT OF THE FIRST SUBSTRATE WITH RESPECT TO THE SECOND SUBSTRATE BASED ON MEASURING A SECOND DETECTED MISALIGNMENT OF THE THIRD ALIGNMENT MARK WITH RESPECT TO THE FOURTH ALIGNMENT MARK USING A THIRD INTERFEROMETRIC PATTERN AND A FOURTH INTERFEROMETRIC PATTERN ASSOCIATED WITH THE SECOND MOIRÉ INTERFEROMETRIC GRATING PAIR, THE MEASURING THE SECOND DETECTED MISALIGNMENT INCLUDING MEASURING A THIRD DISPLACEMENT OF THE THIRD INTERFEROMETRIC PATTERN IN THE FIRST DIRECTION AND A FOURTH DISPLACEMENT OF THE FOURTH INTERFEROMETRIC PATTERN IN THE SECOND DIRECTION.

FIG. 13