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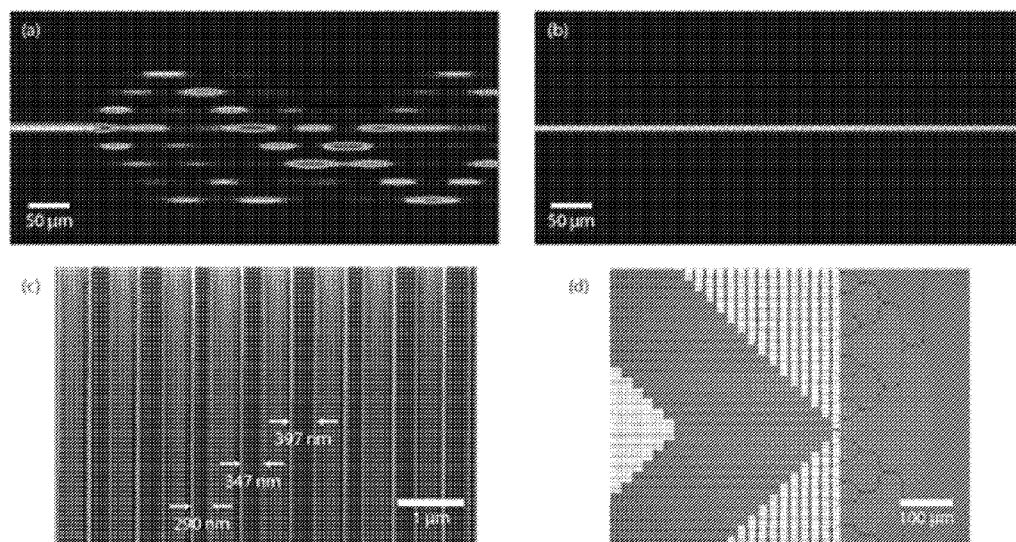


FIG. 1

(57) Abstract: A method of forming an emitting array of waveguides, comprising providing a plurality of waveguides that exhibit different propagation constants so as to ensure that nearby waveguides do not couple evenly over parallel propagation lengths by varying a length in one or more dimensions of respective waveguides, whereby the respective waveguides are phasemismatched with at least their nearest neighbor.



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DENSELY-PACKED OPTICAL PHASED ARRAYS VIA K-VECTOR MISMATCH AND
METAMATERIAL RODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Appl. Ser. No. 62/524,880, filed June 26, 2017, the disclosures of each of which are incorporated herein by reference in their entireties for any and all purposes.

GOVERNMENT RIGHTS

[0002] This invention was made with Government support under award/contract/grant number DARPA-BAA-16-13 awarded by DARPA. The Government has certain rights in the invention.

TECHNICAL FIELD

[0003] Optical phased arrays are described in which the widths of the waveguides vary periodically across the array to avoid coupling. Using index-mismatched waveguides, optical phased arrays with tightly-spaced waveguides of unequal widths but half-wavelength emitter pitch may be used, for example, to provide sidelobe-free beam formation over the entire 180° field of view and beam formation up to 60° off-axis.

BACKGROUND

[0004] Integrated optical phased arrays have gathered significant interest to form and scan laser beams for applications including free-space communications, holography, and light detection and ranging (LIDAR). Those skilled in the art will appreciate that LIDAR is a key enabling sensor for autonomous vehicles, drone navigation, augmented reality, and human-robot interaction but is currently extremely large and expensive. Small, light, and cheap solid-state LIDAR sensors remain desirable. Critical for these applications is the ability to address a single isolated beam over a wide family of angles (field of view); however, most optical phased arrays to date suffer from additional aliased grating lobes at regular angles because their emitters are spaced farther apart than the desired one-half wavelength, limiting the maximum uniquely addressable angle to typically 20-30°. As illustrated in Fig. 1(a), sub-wavelength spacing is difficult to achieve because of strong evanescent coupling between closely-spaced dielectric waveguides.

[0005] In an optical phased array, a large number of regularly-spaced on-chip waveguides (wires for light, or “emitters”, made of any dielectric or semiconductor material) each carry an optical signal, which, after leaving the chip, combine into a single narrow beam. The angle the beam points towards can be controlled by changing the relative phase of each emitter. The spacing between adjacent emitters controls several important properties, primarily (1) the range of unique angles the beam can be pointed to without aliasing and (2) the efficiency with which light can be coupled in reverse back into the array from free space. It is useful for both of these properties to be able to space the waveguides at one-half the light wavelength ($\lambda/2$), but traditionally this is very hard because very closely-spaced waveguides couple between themselves and destroy the desired phase and amplitude profile.

[0006] Several groups, including Tin Komljenovic, et al., “Sparse aperiodic arrays for optical beam forming and LIDAR,” *Opt. Express* **25**, 2511-2528 (2017); D.N. Hutchison et al., “High-resolution aliasing-free optical beam steering,” *Optica* **3**, 887-890 (2016); and David Kwong et al., “1x12 Unequally spaced waveguide array for actively tuned optical phased array on a silicon nanomembrane,” *Appl. Phys. Lett.* **99**, 051104 (2011), have addressed the aliasing problem of large evenly-spaced arrays by using large but unequal spacing between adjacent emitters, which avoids constructive interference towards the off-axis grating lobes. Such groups have also attempted to eliminate grating lobes by using non-uniform spacing on a coarse ($>\lambda/2$) phased array, but this approach lowers the percentage of power in the main beam and also the overlap efficiency of the received reflection. Such designs thus sacrifice power directed toward the target.

[0007] Others, such as W. Song et al. in *Nature Communications*, 6 (2015), p. 7027, have discussed k-vector mismatch. However, Song et al. do not demonstrate their device in a phased array, do not discuss how to transition between coarse-pitch and fine pitch waveguide arrays without coupling, and do not discuss methods for optimizing the overlap efficiency.

[0008] It is desired to provide a much wider range of possible beam emission angles because by allowing $\lambda/2$ emitter spacing and to achieve a higher receive efficiency by enabling the emitter modes to be “close” to each other, thereby minimizing the dead area between emitters where incoming light would not couple back into a waveguide.

[0009] Recently, Jahani et al., “Controlling evanescent waves using silicon photonic all-dielectric metamaterials for dense integration” *Nature Communications* 9:1893 (2018) shown that by placing sub-wavelength metamaterial structures near the waveguide, it is possible to reduce the evanescent tail of the light, thus reducing the crosstalk between adjacent waveguides. By surrounding the main waveguide with metamaterial rods, an increase in the anisotropy of the

material ($\epsilon_z \gg 1$) may be realized such that the decay constant of evanescent waves k_x''/k_0 is increased, thus reducing crosstalk.

SUMMARY

[0010] By varying the widths of the waveguide periodically across an optical phased array (for example, 300 nm, 350 nm, 400 nm, 300 nm, 350 nm, 400 nm, 300 nm, ..., left to right), coupling of light between waveguides is avoided. Changing the waveguide width changes its effective index, and waveguides with different effective indices couple much more weakly. A set of two or more widths is chosen (three is typical) so that waveguides with the same width are spaced far enough apart to not couple even though their effective indices match. The width of the waveguides are chosen both to maximize the difference in effective index (*i.e.* minimize the coupling) and to maximize the fill factor of the mode to maximize the efficiency of coupling from a free-space plane wave back into the waveguides. By segmenting the waveguide we can alternate between the different widths and still maintain crosstalk free light propagation. This allows for embedding grating in proximity to the waveguides, emitting light out-of-plane of the device. By designing the period of the grating for each propagation constant (for each waveguide width), it is possible to direct the out-going light to the same direction. By embedding metamaterial rods in between the waveguides we further reduce the crosstalk between waveguides, allowing for longer propagation free of crosstalk.

[0011] Exemplary embodiments are also characterized by transitioning from a coarsely-spaced array of waveguides with equal width to the above described tightly-spaced array of unequal widths. First, the waveguides are tapered while still coarsely spaced to their final widths. Then, the waveguides are bent 90 degrees with equal radii, with the position of the bend staggered such that the bend ends with the desired fine spacing (with the array now rotated 90 degrees from the input). The bend radii are designed so that the waveguide effective index in the bend is not significantly perturbed from its straight-waveguide value and also avoids coupling into higher-order modes.

[0012] In an exemplary embodiment, a method of forming an optical phased array half-wavelength uniform emitter pitch comprises providing a plurality of waveguides that are phase mismatched so as to ensure that nearby waveguides do not couple even over long parallel propagation lengths by varying the widths of respective waveguides in a regular pattern whereby the respective waveguides are phase-mismatched with at least their nearest neighbor and their second-nearest neighbor waveguide. In the exemplary embodiments, the widths of the respective

waveguides are varied periodically across the optical phased array. For example, the widths of the respective waveguides may be varied in a pattern of repeating widths of 300 nm, 350 nm, and 400 nm.

[0013] In further exemplary embodiments, the method includes tapering the respective waveguides to a tightly-spaced optical phased array having the widths of respective waveguides in the regular pattern by tapering each waveguide to its width in the pattern and bending each waveguide approximately 90° from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the regular pattern. In the exemplary embodiments, the bend radii is selected whereby a waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value and whereby coupling of light into higher modes is substantially avoided.

[0014] An optical phased array resulting from such a method has a half-wavelength uniform emitter pitch and includes a plurality of waveguides that are phase mismatched so as to ensure that nearby waveguides do not couple even over long parallel propagation lengths. The waveguides are disposed in a regular array pattern whereby the widths of the respective waveguides are varied in a regular pattern such that the respective waveguides are phase-mismatched with at least their nearest neighbor and their second-nearest neighbor waveguide. In the exemplary embodiments, the widths of the respective waveguides are varied periodically in, for example, a pattern of repeating widths of 300 nm, 350 nm, and 400 nm. The respective waveguides are tapered to a tightly-spaced optical phased array having a width of the respective waveguide in the regular pattern, and each respective waveguide is bent approximately 90° from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the regular pattern. In exemplary embodiments, the waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value.

[0015] In an exemplary embodiment, a method of forming an optical phased array half-wavelength uniform emitter pitch comprises providing a plurality of segments of waveguides that are phase mismatched so as to ensure that nearby waveguides do not couple and embedding gratings on top or side of the waveguide to emit light out-of-plane.

[0016] In an exemplary embodiment, a method of forming an optical phased array half-wavelength uniform emitter pitch comprises providing a plurality of segments of waveguides that are phase mismatched and metamaterial rods in between so as to ensure that nearby waveguides do not couple and embedding gratings on top or side of the waveguide to emit light out-of-plane.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The above and other objects and advantages of the invention will be apparent to those skilled in the art based on the following detailed description in conjunction with the appended figures, of which:

[0018] Fig. 1(a) illustrates eigenmode expansion simulation of power propagation in a 0.5 mm-long, 8 waveguide array with 775 nm pitch and equal 400 nm widths.

[0019] Fig. 1(b) illustrates propagation in an exemplary 300, 350, and 400 nm width array, with light launched into a single 300 nm width waveguide, showing negligible coupling between adjacent waveguides over the same length.

[0020] Fig. 1(c) illustrates a scanning electron micrograph of the fabricated waveguide array with unequal widths.

[0021] Fig. 1(d) illustrates an optical microscope image of a splitter tree and a thermo-optic phase shifter array.

[0022] Fig. 2(a) illustrates measured far-field optical power versus angle for several different beam target angles.

[0023] Fig. 2(b) illustrates simulated far-field beam profiles for a perfectly-aligned output phase.

[0024] Fig. 3 is a schematic illustrating the alternate widths idea. Widths are cycled along the emitter length reducing the crosstalk while matching the phase velocity.

[0025] Fig. 4 is a schematic showing main waveguide's, 1st neighbors', and 2nd neighbors' widths are: 450nm, 440nm and 450nm, respectively and illustrating minimized crosstalk between waveguides with half-wavelength pitch.

[0026] Fig. 5 illustrates coupling between waveguide, where a main waveguide have more than 90% of initial power after 2 millimeters.

[0027] Fig. 6 illustrates power vs. angle as a function of pitch in accordance with aspects of the present disclosure.

[0028] Fig. 7 illustrates coupling without metamaterial rods and showing emitter length due to the large crosstalk between waveguides.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0029] An exemplary embodiment of a method and device for recycling light without resonance is described below with respect to Figs. 1-2. Those skilled in the art will appreciate

that the steps and systems described are for exemplary purposes only and are not limited to the specific processes and systems described.

[0030] A phased array with true half-wavelength uniform emitter pitch is provided by designing waveguides that are phase mismatched to ensure that nearby waveguides do not couple even over long parallel propagation lengths. This phase mismatch is created by varying the width, and thus effective index, of the waveguides in a regular pattern. In exemplary embodiments, the waveguides are phase-mismatched with both their nearest neighbor and with their second-nearest neighbor as described by Weiwei Song et al., “High-density waveguide superlattices with low crosstalk,” *Nat. Commun.* 6, 7027 (2015), by cycling through a set of, for example, three widths (*e.g.*, 300, 350, and 400 nm, in sequence). As illustrated in Fig. 1(b), for the < 0.5 mm propagation lengths used experimentally, it was found that coupling between third-nearest neighbors (waveguides with equal width separated by 1.5λ) is negligible and power propagates only in the waveguide it was launched into.

[0031] To show phased-array beam forming, a 32-channel end-fire device was fabricated in 250 nm-thick silicon on insulator (Fig. 1(c)). The input power was equally split among each waveguide using a tree of 1x2 MMI splitters, then the phase on each 400 nm-wide output waveguide was controlled with a thermal phase shifter including a 50 nm-thick platinum wire separated from the waveguide with 1 μm of PECVD SiO_2 . Heaters were separated laterally by 20 μm to minimize thermal crosstalk. After the phase shifters, each waveguide was tapered to its final width and the waveguides were brought together to the final 775 nm pitch with a nested 90° bend. This waveguide array was routed to the edge of the chip where it emits through a reactive ion etched facet as described by Jaime Cardenas et al., “High coupling efficiency etched facet tapers in silicon waveguides,” *IEEE Photon. Technol. Lett.* 26, 2380-2382 (2014). Each micro-heater was connected to a bond pad with thick aluminum wires, wire bonded to a printed circuit board, and driven with a channel of a digital to analog converter. Fig. 1(d) illustrates an optical microscope image of a splitter tree and a thermo-optic phase shifter array.

[0032] The phases of the end-fire beam were aligned by placing a single-element photodiode at the desired beam position in the far field (20 cm away from the chip facet) and a gradient-free local maximization algorithm of the type, for example, disclosed by M.J.D. Powell, “An efficient method for finding the minimum of a function of several variables without calculating derivatives,” *Comput. J.* 7, 155-162 (1964), was performed to find the set of phase shifter voltages that maximize power at the detector, in effect maximizing the output Strehl ratio. The angular distribution of output light was then measured by mechanically rotating the same detector about the chip output facet in the waveguide plane. Unlike lens-based Fourier imaging,

this mechanical setup allowed measurement of the complete 180° beam pattern because measurement was not limited by the lens numerical aperture.

[0033] Fig. 2(a) illustrates grating lobe-free beam formation over the entire 180° field of view using this arrangement. Because only roughly 75% of the phase shifters could be controlled, the measured side lobe level is relatively high, but it can be reduced with better phase control as shown in Fig. 2(b). By repeating the optimization process at several different target beam angles, steering of the beam up to 60° off-axis, limited only by the single-waveguide emission envelope and not by aliasing effects, was achieved.

[0034] Those skilled in the art will appreciate that the system and method described herein has many applications including light detection and ranging (LIDAR) applications such as beam steering without movable mirrors, direction sensors for self-driving vehicles, and the like. Other applications include free-space optical communications, spatial light modulators, and laser projection displays. Those skilled in the art will further appreciate that the methods described herein may be used with designs for gratings to create a beam scanned in two dimensions.

[0035] The present disclosure includes at least the following aspects:

[0036] Aspect 1: A method of forming an emitting array of waveguides, comprising configuring a plurality of waveguides that exhibit different propagation constants so as to ensure that nearby waveguides minimize crosstalk over parallel propagation lengths by varying one or more of the width or height of one or more of the plurality of waveguides, whereby at least one of the waveguides is phase-mismatched with at least a nearest and second nearest neighbor. As used herein, nearby may be defined as on or adjacent. As described herein, nearby may comprise nearest neighbor or second nearest neighbor. As used herein, adjacent means on or in proximity to and does not foreclose intervening layers including air or fluid.

[0037] Aspect 2: A method of forming an array of segment waveguides having gratings, comprising configuring a plurality of waveguides that exhibit different propagation constants so as to ensure that nearby waveguides minimize crosstalk over parallel propagation lengths by varying one or more of the width or height of one or more of the plurality of waveguides, whereby at least one of the waveguides is phase-mismatched with at least a nearest and second nearest neighbor.

[0038] Aspect 3: The method of claim 2, wherein the gratings are configured for each segment's propagation constant to match the direction of emission from all segments.

[0039] Aspect 4: The method of any one of aspects 1-3, further comprising disposing one or more metamaterial rods between two or more of the waveguides.

[0040] Aspect 5: The method of aspect 4, wherein the metamaterial rods are effective to decrease the crosstalk between the waveguides in the array, allowing for longer propagation length while minimizing crosstalk between the waveguides.

[0041] Aspect 6: The method of any one of aspects 1-5, wherein one or more of the width or height of the one or more waveguides is varied periodically across the optical phased array.

[0042] Aspect 7: The method of any one of aspects 1-6, wherein the propagation constant comprises a real value, an imaginary value, or a combination thereof.

[0043] Aspect 8: The method of any one of aspects 1-2, further comprising one or more dielectric rods disposed adjacent to the waveguides to reduce crosstalk between waveguides, allowing for short pitch between waveguides.

[0044] Aspect 9: The method of aspect 5 or 8, wherein the rods comprise a different material than the waveguides.

[0045] Aspect 10: The method of aspect 5 or 8, further comprising a cladding disposed adjacent the waveguide, wherein a material forming the rods has a dielectric constant that is larger than a dielectric constant of the cladding of the waveguide, thereby increasing anisotropy along the array length and perpendicular to it.

[0046] Aspect 11: A method as in aspect 1, further comprising tapering the waveguides to a tightly-spaced optical phased array having the length in one or more dimensions of respective waveguides in a pattern by tapering each waveguide to its length in one or more dimensions in the pattern and bending each waveguide approximately 90° from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the pattern.

[0047] Aspect 12: A method as in aspect 11, wherein the bend radii is selected whereby a waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value and whereby coupling of light into higher modes is substantially avoided.

[0048] Aspect 13: An optical phased array comprising a plurality of waveguides that are phase mismatched so as to ensure that adjacent waveguides minimize crosstalk over parallel propagation lengths, the waveguides disposed in an array pattern whereby a length in one or more dimensions of respective waveguides are varied in a pattern such that the respective waveguides are phase-mismatched with at least their nearest neighbor.

[0049] Aspect 14: An optical phased array as in aspect 13, wherein the length in one or more dimensions of the respective waveguides are varied periodically in the array pattern.

[0050] Aspect 15: An optical phased array as in aspect 13, wherein the respective waveguides are tapered to a tightly-spaced optical phased array having the length in one or more dimensions of the respective waveguide in the pattern, and wherein each respective waveguide is bent from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the pattern.

[0051] Aspect 16: An optical phased array as in aspect 15, wherein the waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value.

[0052] As an illustrative example, it is understood that conventional operations often use arrays of waveguides/emitters with gratings to achieve two-dimensional beam steering: 1st dimension is done by controlling the phase of the light in the emitters and 2nd dimension steering is done by varying the input wavelength. This allows for steering the light from the array to any arbitrary point in space. By using the wavelength to steer the beam you considerably reduce the control signals and area.

[0053] The present disclosure allows for a $\frac{\lambda}{2}$ spacing between the waveguides. The short spacing may be import for two reasons:

- 1) It increases the filling factor – percentage of area occupied by emitters/receivers to entire array area in the array. Affect the efficiency of transmitted and received signals
- 2) Beam steering range – see Fig. 6.

[0054] As an illustrative example, the closer the waveguides are placed, the larger the beam steering is and the higher the efficiency of the main beam. However, unlike their Radio Frequency counterparts, pitch (distance between emitters) of existing optical phased array is limited to $\sim 2 \mu\text{m}$ due the strong crosstalk of the light propagating in the waveguides (in our case, wavelength is usually $\sim 1.5\text{-}1.6 \mu\text{m}$).

[0055] It is common to use gratings for 2D beam steering, which are sensitive to the phase velocity of light in the emitters. The idea of k-vector mismatch is challenging to implement because it also affects the phase velocity of the light in the emitters. The present disclosure may address these shortcomings by alternating the widths (or any length dimension) of the waveguides along the gratings (See Figs. 3-5). In order to further reduce the cross talk between waveguides the present disclosure may use metamaterial rods adjacent to the main waveguide.

[0056] The k vector mismatch combined with the metamaterial rods enable long emitters with low crosstalk at minimal pitch. Fig 4 has a simulation of cross talk between a main

waveguide and 1st and 2nd neighbor. Fig. 7 shows the large coupling without using the metamaterial rods.

CLAIMS

What is Claimed:

1. A method of forming an emitting array of waveguides, comprising configuring a plurality of waveguides that exhibit different propagation constants so as to ensure that nearby waveguides minimize crosstalk over parallel propagation lengths by varying one or more of the width or height of one or more of the plurality of waveguides, whereby at least one of the waveguides is phase-mismatched with at least a nearest and second nearest neighbor.
2. A method of forming an array of segment waveguides having gratings, comprising configuring a plurality of waveguides that exhibit different propagation constants so as to ensure that nearby waveguides minimize crosstalk over parallel propagation lengths by varying one or more of the width or height of one or more of the plurality of waveguides, whereby at least one of the waveguides is phase-mismatched with at least a nearest and second nearest neighbor.
3. The method of claim 2, wherein the gratings are configured for each segment's propagation constant to match the direction of emission from all segments.
4. The method of any one of claims 1-3, further comprising disposing one or more metamaterial rods between two or more of the waveguides.
5. The method of claim 4, wherein the metamaterial rods are effective to decrease the crosstalk between the waveguides in the array, allowing for longer propagation length while minimizing crosstalk between the waveguides.
6. The method of any one of claims 1-5, wherein one or more of the width or height of the one or more waveguides is varied periodically across the array.
7. The method of any one of claims 1-6, wherein the propagation constant comprises a real value, an imaginary value, or a combination thereof.

8. The method of any one of claims 1-2, further comprising one or more dielectric rods disposed adjacent to the waveguides to reduce crosstalk between waveguides, allowing for short pitch between waveguides.
9. The method of claim 5 or 8, wherein the rods comprise a different material than the waveguides.
10. The method of claim 5 or 8, further comprising a cladding disposed adjacent the waveguide, wherein a material forming the rods has a dielectric constant that is larger than a dielectric constant of the cladding of the waveguide, thereby increasing anisotropy along the array length and perpendicular to it.
11. A method as in claim 1, further comprising tapering the waveguides to a tightly-spaced optical phased array having the length in one or more dimensions of respective waveguides in a pattern by tapering each waveguide to its length in one or more dimensions in the pattern and bending each waveguide approximately 90° from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the pattern.
12. A method as in claim 11, wherein the bend radii is selected whereby a waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value and whereby coupling of light into higher modes is substantially avoided.
13. An optical phased array comprising a plurality of waveguides that are phase mismatched so as to ensure that adjacent waveguides minimize crosstalk over parallel propagation lengths, the waveguides disposed in an array pattern whereby a length in one or more dimensions of respective waveguides are varied in a pattern such that the respective waveguides are phase-mismatched with at least their nearest neighbor.
14. An optical phased array as in claim 13, wherein the length in one or more dimensions of the respective waveguides are varied periodically in the array pattern.

15. An optical phased array as in claim 13, wherein the respective waveguides are tapered to a tightly-spaced optical phased array having the length in one or more dimensions of the respective waveguide in the pattern, and wherein each respective waveguide is bent from an input with equal radii with a position of a bend staggered such that the bend ends with a desired spacing of the waveguides in the pattern.
16. An optical phased array as in claim 15, wherein the waveguide effective index in the bend is not significantly perturbed from a straight waveguide effective index value.

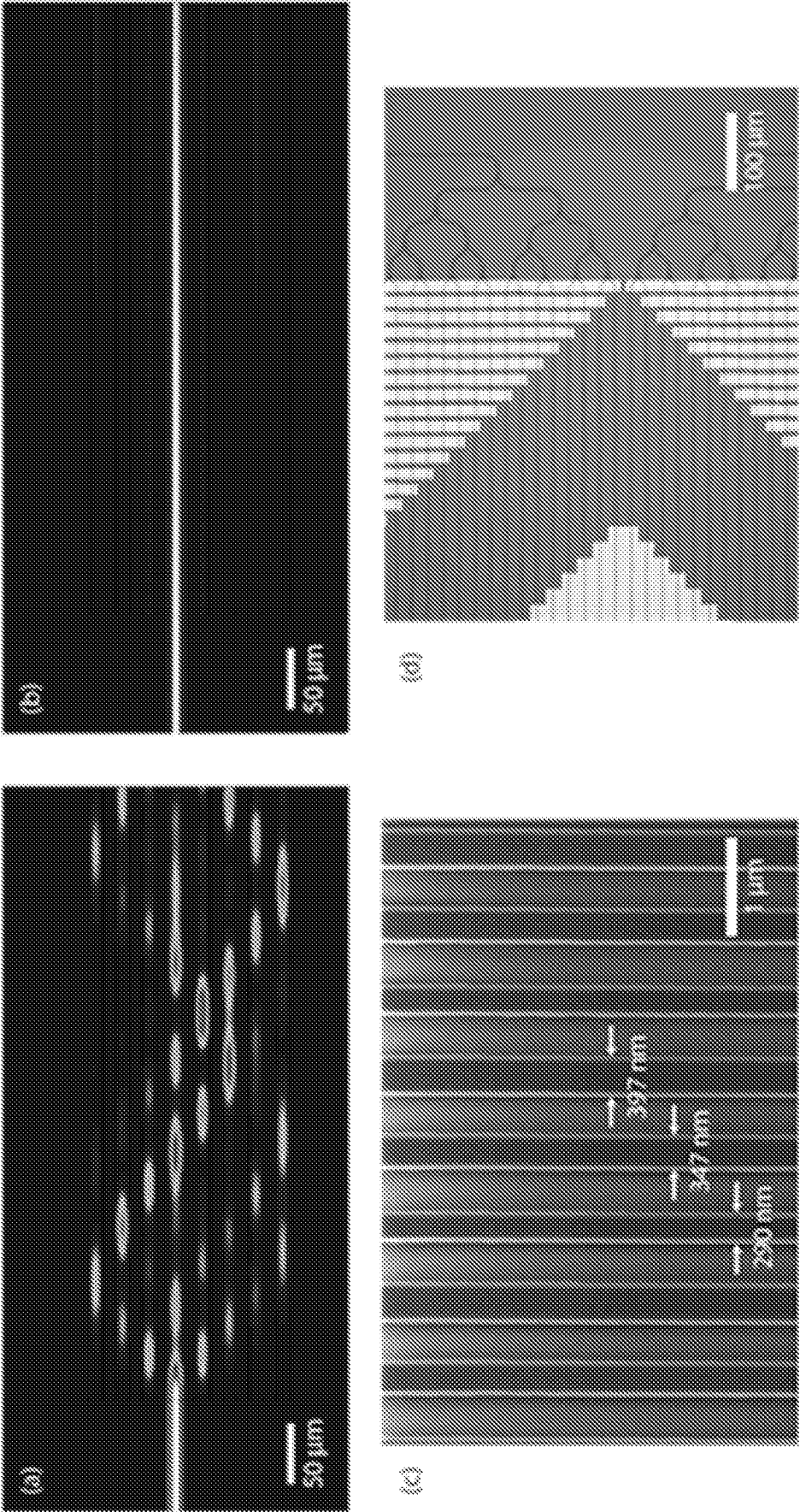


FIG. 1

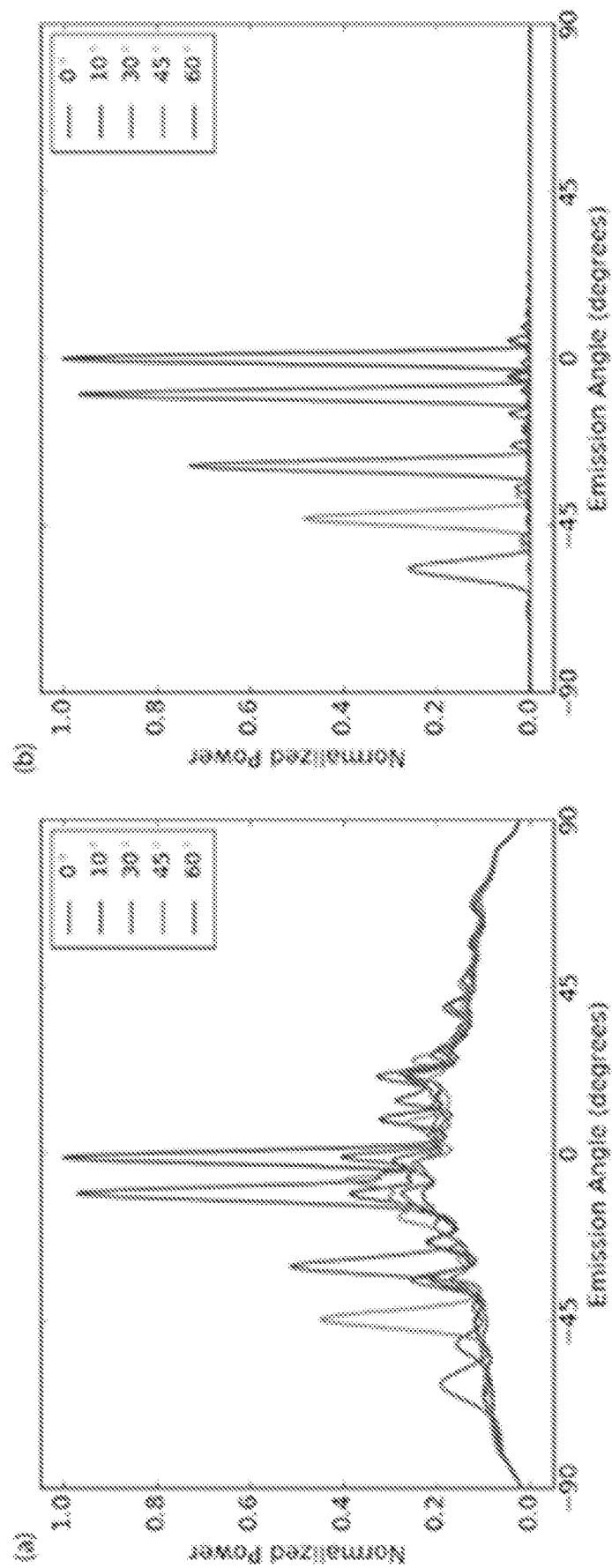
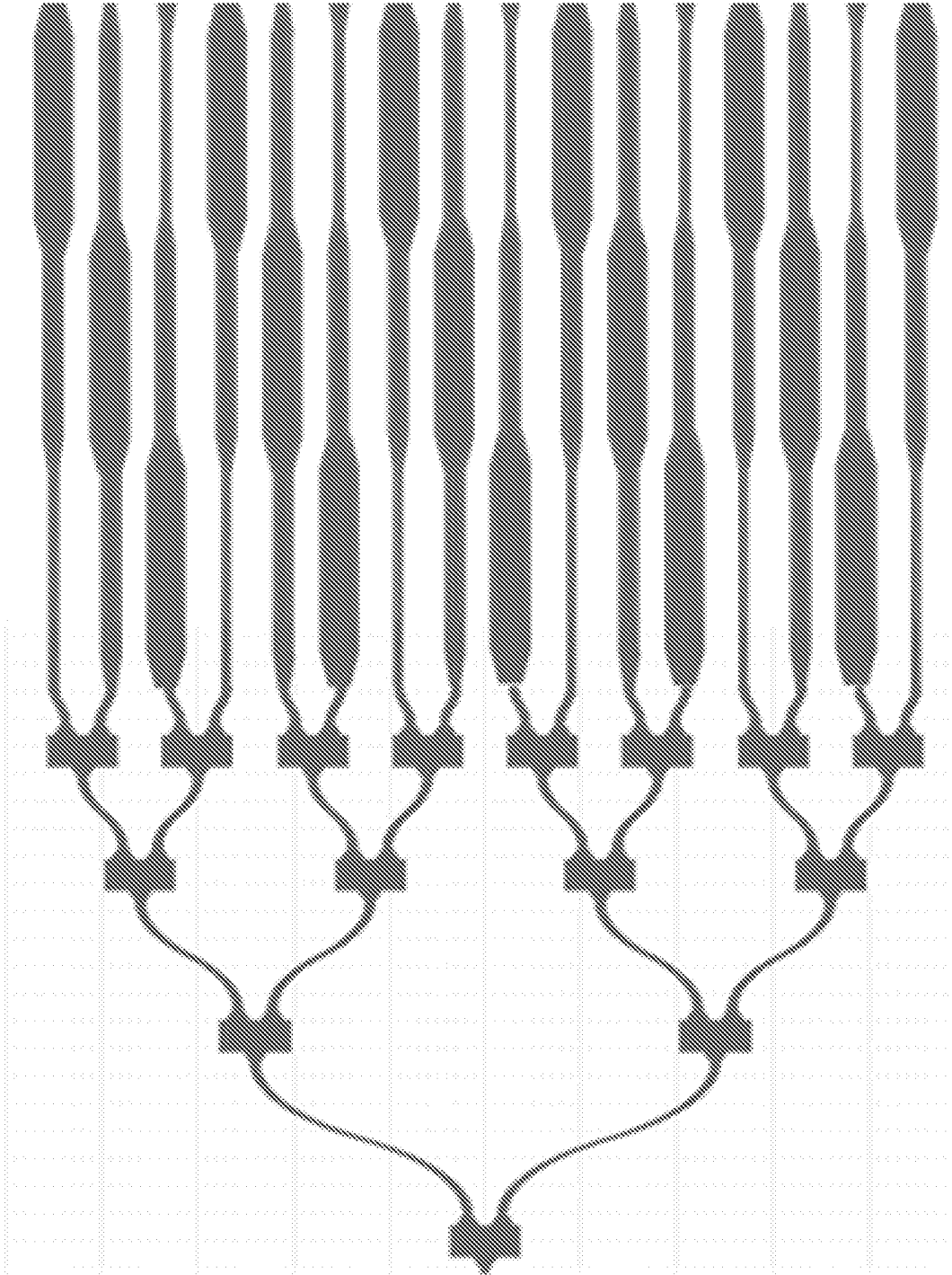


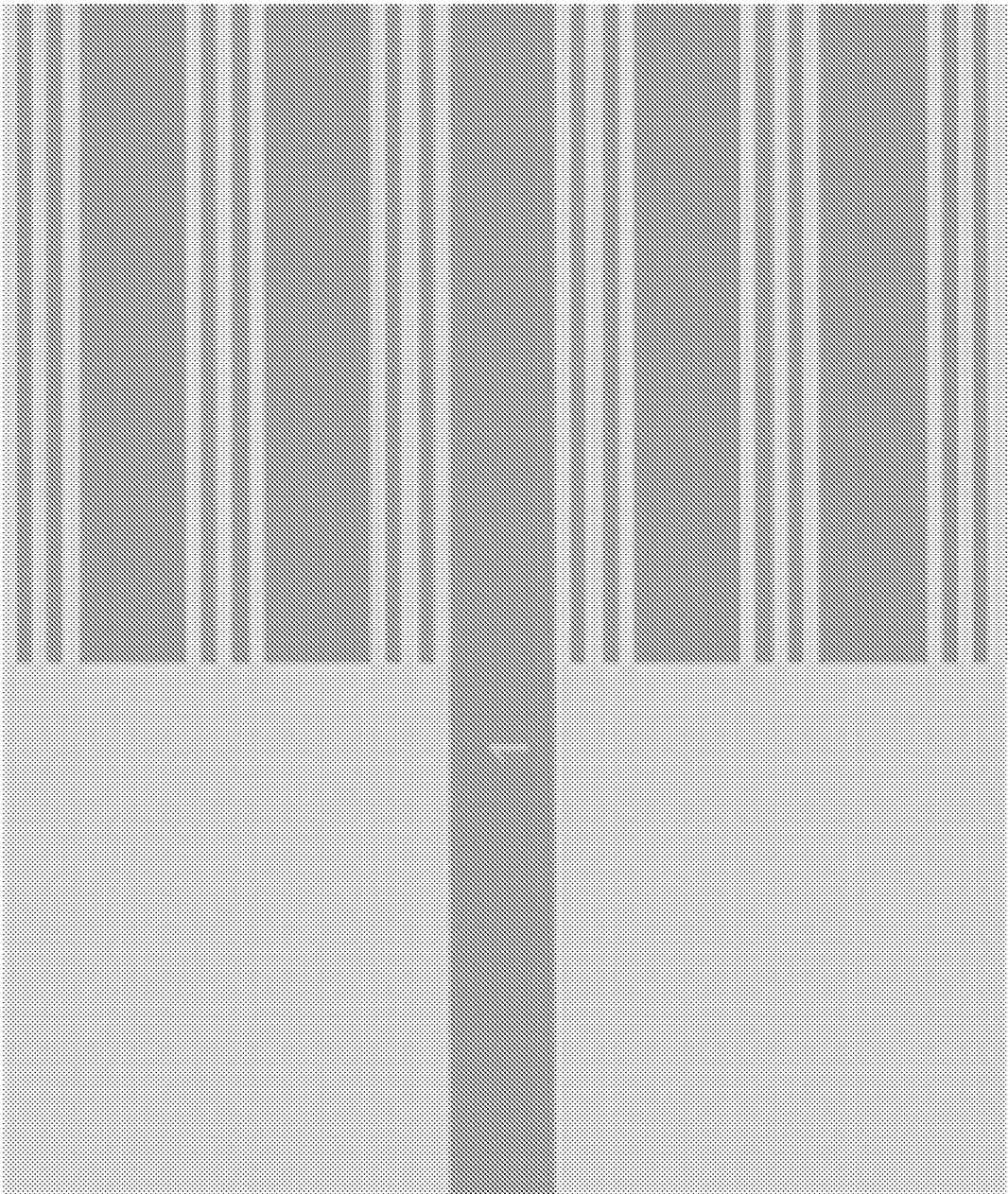
FIG. 2

FIG. 3



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FIG. 4



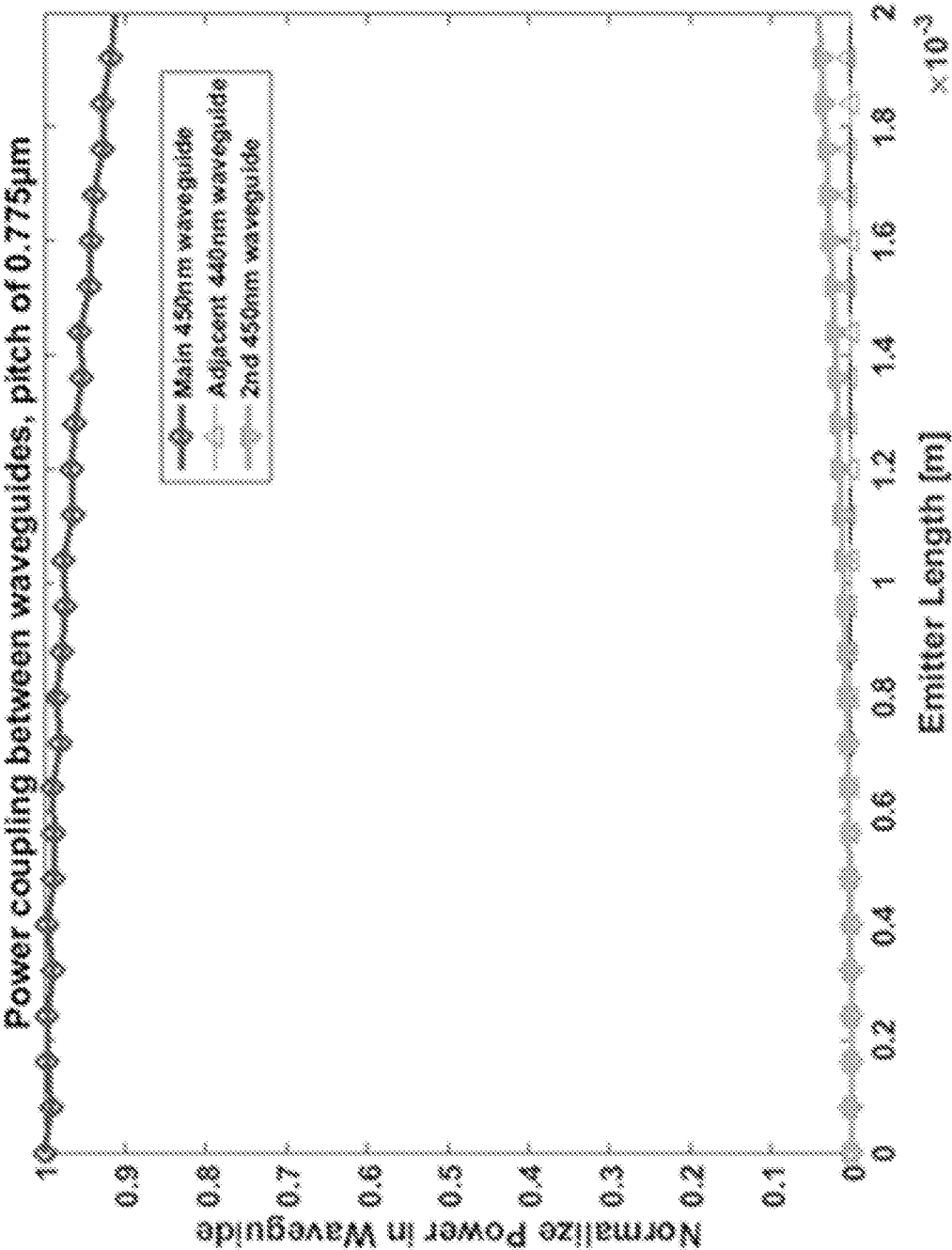


FIG. 5

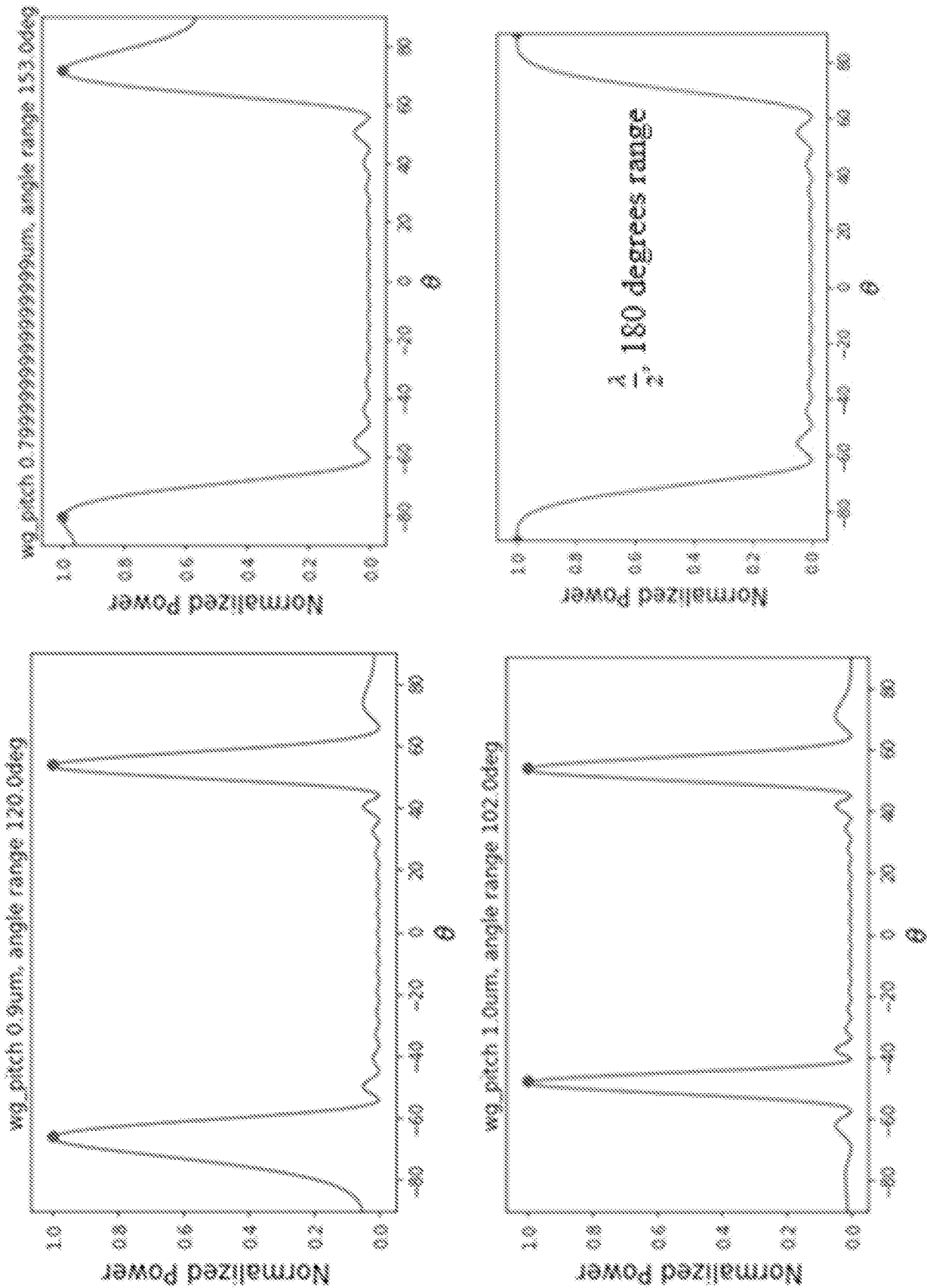


FIG. 6

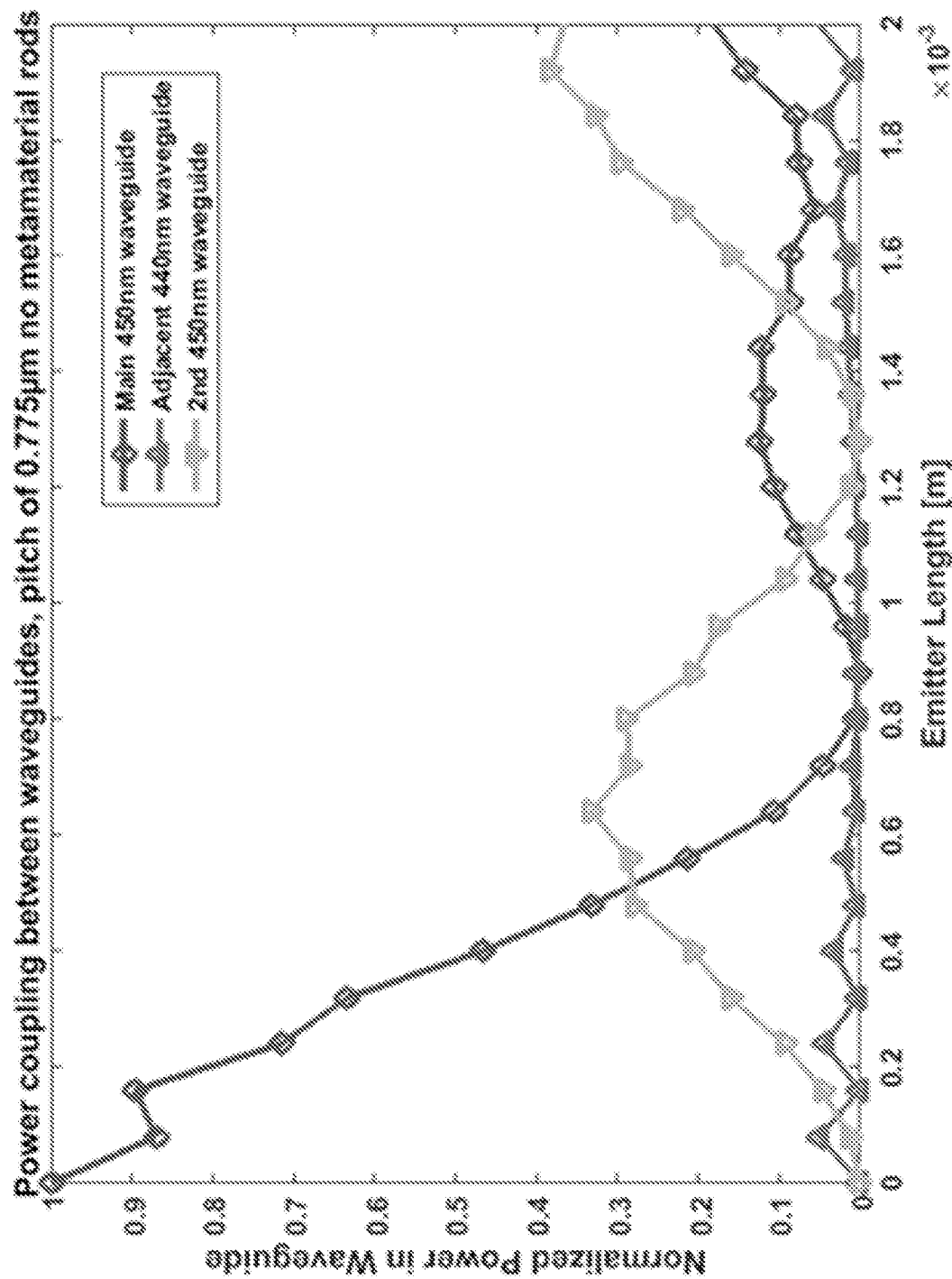


FIG. 7