

A DUAL-MODE WAVEGUIDE ANTENNA

TECHNICAL FIELD

[0001] This application relates to a dual-mode waveguide antenna for single beam emission in an optical phased array.

BACKGROUND

[0002] Due to burgeoning developments in the fields of autonomous driving, facial recognition, free-space communications, and augmented reality (AR), the demands for integrated optical phased arrays (OPAs) that are used in light detection and ranging (LiDAR) systems has increased year over year. Compared to traditional radar array systems which manipulate optical beams in a mechanical manner, a phase controlled optical waveguide array system which employs OPAs are able to manipulate the beam angle and waveform emitted by the OPAs in an inexpensive and non-mechanical manner, i.e., by digitally controlling the phase of the optical signals that are provided to the OPAs.

[0003] An OPA that is used for image scanning generally projects an optical beam to a single direction in response to an optical signal with a single operating wavelength. If the optical signal contains more than one operating wavelength, the resulting optical beams will appear at more than one angle. In such a situation, multiple OPAs are normally employed, with each OPA exclusively dedicated to the control of each operating wavelength.

[0004] For example, in the context of Red-Green-Blue (RGB) imaging, the resulting beam that is formed from a conventional OPA at different wavelengths ends up with different emission angles - as illustrated in Figure 1 (which uses conventional OPAs 105). As shown, an optical signal with a red wavelength has a red emission angle θ_R , an optical signal with a green wavelength has a green emission angle θ_G , and an optical signal with a blue wavelength has a θ_B emission angle. If the RGB colors are to be concurrently superimposed upon one another, either three separate OPAs are needed to control the generation of each color individually, or additional phase correction has to be implemented to offset the angular differences between the resulting beams. The downside to this is that the former approach would increase the fabrication difficulty of the overall system or the device's footprint while the latter approach

requires a complicated control mechanism. Either way, the resulting image scanning process would only be achieved at the cost of system compactness and robustness.

[0005] Despite efforts of those skilled in the art, current techniques are still unable to provide a waveguide antenna for an optical phase array that can produce a single emission angle when two separate optical signals with differing wavelengths are beamed through it.

SUMMARY

[0006] In one aspect, the present application discloses a dual-mode waveguide antenna. The dual-mode antenna disclosed in the present application comprises a straight section configured to receive an optical signal and a periodic sinusoidal tapered section optically coupled to the straight section whereby the periodic sinusoidal tapered section is configured to project the optical signal into an optical beam. Further, a period Λ of the periodic sinusoidal tapered section is configured to be longer than an operating wavelength λ of the optical signal, a width W_{WG} of the straight section is configured to be smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is configured to be equal to the width W_{WG} of the straight section.

[0007] In a further embodiment of this aspect, a width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section is determined based on the width W_{WG} of the straight section, the maximum width W_{MAX} and the minimum width W_{MIN} of the periodic sinusoidal tapered section.

[0008] In another aspect, the present application discloses a method of forming a dual-waveguide antenna. The method comprising the step of forming a straight section of the dual-waveguide antenna whereby the straight section is configured to receive an optical signal and a step of forming a periodic sinusoidal tapered section of the dual-waveguide antenna such that the periodic sinusoidal tapered section is optically coupled to the straight section whereby the periodic sinusoidal tapered section is configured to project the optical signal into an optical beam. Further, a period Λ of the periodic sinusoidal tapered section is formed such that the period Λ is longer than an operating wavelength λ of the optical signal, a width W_{WG} of the straight section is formed such that the width W_{WG} is smaller than a maximum width W_{MAX} of

the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is formed such that the width at the midpoint of each period Λ is equal to the width W_{WG} of the straight section.

[0009] In a further embodiment of this another aspect, a width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section is determined based on the width W_{WG} of the straight section, the maximum width W_{MAX} and the minimum width W_{MIN} of the periodic sinusoidal tapered section.

[0010] In yet another aspect, the present application discloses an optical phased array system that comprises a plurality of dual-mode waveguide antennas. Each dual-mode waveguide antenna in the optical phased array system comprises a straight section configured to receive an optical signal and a periodic sinusoidal tapered section optically coupled to the straight section whereby the periodic sinusoidal tapered section is configured to project the optical signal into an optical beam. Further, a period Λ of the periodic sinusoidal tapered section is configured to be longer than an operating wavelength λ of the optical signal, a width W_{WG} of the straight section is configured to be smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is configured to be equal to the width W_{WG} of the straight section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Various embodiments of the present disclosure are described below with reference to the following drawings:

Figure 1 illustrates the beam forming of a Red-Green-Blue (RGB) imaging system using conventional waveguide antennas in an optical phased array (OPA) as known in the art;

Figure 2A illustrates a top-view line drawing of a dual-mode waveguide antenna in accordance with an embodiment of the present disclosure;

Figure 2B illustrates a top-view schematic (not drawn to scale) of the dual-mode waveguide antenna illustrated in Figure 2 in accordance with an embodiment of the present disclosure;

Figure 3 illustrates the top view of the discretization of period Λ of the periodic sinusoidal tapered section of the dual-mode waveguide antenna into N parts along the longitudinal axes of the periodic sinusoidal tapered section in accordance with an embodiment of the present disclosure;

Figure 4 illustrates a flowchart that sets out the process or method for forming the dual-mode waveguide antenna in accordance with an embodiment of the present disclosure;

Figure 5 illustrates a simulated far field diffraction pattern of the dual-mode waveguide antenna when the optical signal provided to the dual-mode waveguide antenna has an operating wavelength of 633nm;

Figure 6 illustrates a simulated far field diffraction pattern of the dual-mode waveguide antenna when the optical signal provided to the dual-mode waveguide antenna has an operating wavelength of 532nm;

Figure 7 illustrates a simulated far field diffraction pattern of the dual-mode waveguide antenna when the periodic sinusoidal tapered section of the dual-mode waveguide antenna is replaced with a periodic multi-stepped tapered section and when the optical signal provided to the dual-mode waveguide antenna has an operating length of 532nm; and

Figure 8 illustrates the normalized power remaining in the waveguide antenna after optical signals having an operating wavelength of 532nm and 633nm respectively have propagated 50 μ m along the longitudinal axis of the dual-mode waveguide antenna.

DETAILED DESCRIPTION

[0012] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0013] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0014] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0015] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0016] As used herein, “comprising” means including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0017] As used herein, “consisting of” means including, and limited to, whatever follows the phrase “consisting of”. Thus, use of the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0018] A top-view line drawing of a dual-mode waveguide antenna for use in optical phased arrays (OPAs) is illustrated in Figure 2A. In embodiments of the disclosure, a plurality of dual-mode waveguide antenna 200 may be used in the OPA to produce a single emission angle when two separate optical signals with differing wavelengths are beamed through the OPA. As illustrated, the structure of dual-mode waveguide antenna 200 comprises waveguide 210 and cladding 205, which may comprise a substrate and a superstrate. As shown in Figure 2A, dual-mode waveguide antenna 200 comprises of two sections: straight section 221 and periodic sinusoidal tapered section 222 that is optically coupled to straight section 221.

[0019] One skilled in the art will recognize that periodic sinusoidal tapered section 222 may be defined as a type of waveguide in which the width variation of the waveguide along its longitudinal axis follows a sinusoidal pattern with a period Λ (as shown in Figure 2A). In other words, in section 222, the width $W(x)$ of the waveguide varies periodically (with a period Λ) along its longitudinal axis with a sinusoidal function. The sinusoidal tapering creates a gradual and smooth variation in the refractive index profile and in the dimensions of the waveguide. This in turn affects the antenna's guided mode propagation characteristics by minimizing reflections or losses caused by abrupt transitions in the waveguide. In another embodiment of this disclosure, periodic sinusoidal tapered section 222 may be described as a type of

symmetrical waveguide comprising a first complementary portion and a second complementary portion. In this embodiment, the first complementary portion is substantially symmetrical to the second complementary portion along a line of symmetry 250 of waveguide 210, and this line of symmetry 250 is parallel with the longitudinal axis of waveguide 210. One skilled in the art will also recognize that straight section 221 is a type of waveguide in which the width of the waveguide remains constant along its longitudinal axis.

[0020] In operation, straight section 221 is configured to receive an optical signal having a fixed operating wavelength. As periodic sinusoidal tapered section 222 is optically coupled to straight section 221, section 222 is then configured to project the optical signal into an optical beam along an emission angle.

[0021] In embodiments of the present disclosure, a period Λ of the periodic sinusoidal tapered section 222 was designed to be longer than an operating wavelength λ of the optical signal received by straight section 221. The reason for having such a lengthy period Λ of the periodic sinusoidal tapered section 222 was to allow higher order diffractions to match up with each other so that the emission angles of optical signals with different wavelengths may be unified. This reduces the error that occurs when different wavelengths emit from the waveguide antenna at the same angle.

[0022] In further embodiments of the present disclosure, a width W_{WG} of straight section 221 was designed to be smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section 222 and to be larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section 222, i.e., $W_{MIN} < W_{WG} < W_{MAX}$. In still further embodiments of the present disclosure, a width at a midpoint of each period Λ of periodic sinusoidal tapered section 222 was designed to be equal to the width W_{WG} of straight section 221. When the above design conditions of waveguide 200 are met, this ensures that even when the period Λ of periodic sinusoidal tapered section 222 is long (which generally means higher probability of exciting higher diffraction orders), the high order diffractions are still suppressed, and the unwanted side lobes may be effectively cleared from the far field projection.

[0023] Figure 2B illustrates a top-view schematic (not drawn to scale) of the dual-mode waveguide antenna illustrated in Figure 2A in accordance with an embodiment of the present

disclosure. As shown, dual-mode waveguide antenna 200 similarly comprises two sections: straight section 221 and periodic sinusoidal tapered section 222, and the widths of straight section 221 and periodic sinusoidal tapered section 222 are designed as described in the sections above.

[0024] In order to facilitate the process of designing dual-mode waveguide antenna 200, a period Λ of periodic sinusoidal tapered section 222 is divided into N parts along a longitudinal axis of waveguide 200, i.e., along the x -axis of waveguide 200 as illustrated in Figure 3.

[0025] Figure 4 illustrates process 400 for obtaining the optimum values of the widths of waveguide 200 and of the length of period Λ in accordance with embodiments of the present disclosure, whereby process 400 may be implemented in a computing module (not shown) or by modules and/or components in a computer system (not shown).

[0026] Process 400 begins at step 402. At step 402, process 400 generates an effective refractive index n_{eff} database for a set of waveguides whereby each waveguide comprises only straight section 221. In this database, the widths W_{WG} of these waveguides are set to be between 200nm and 1000nm. One skilled in the art will recognize that the width W_{WG} may comprise other values without departing from this disclosure. Optical signals having an operating wavelength of λ_1 and λ_2 are respectively propagated through each of the waveguides in this set. The effective refractive indexes n_{eff} associated with each of the waveguides are then obtained and recorded in the refractive index n_{eff} database for each of the optical signals and their respective wavelengths.

[0027] Additionally, at step 402, process 400 identifies widths W_{WG} of waveguides from the effective refractive index n_{eff} database that could in theory physically support a fundamental mode of an operating wavelength and no more than two higher-order modes for one polarization at the operating wavelength. Such waveguides are then added to a database titled “sub-library 1”.

[0028] Further, at step 402, process 400 also identifies widths W_{WG} of waveguides from the effective refractive index n_{eff} database that could in theory physically support both the fundamental mode of an operating wavelength and four higher order modes for one polarization

at the operating wavelength. Such waveguides are then added to a database titled “sub-library 2”. In embodiments of the disclosure, the width W_{WG} of the straight section may be 500 nm and the value assigned to the N parts of period Λ is $N = 100$. One skilled in the art will recognize that other values may be used without departing from this disclosure. Once this is done, process 400 then progresses to step 404.

[0029] At step 404, process 400 will randomly choose a value for the minimum width W_{MIN} of the periodic sinusoidal tapered section from sub-library 1 and a value for the maximum width W_{MAX} of the periodic sinusoidal tapered section from sub-library 2, along with their associated effective refractive indexes. Process 400 will also assign a value to the width W_{WG} of the straight section and a value to N parts of period Λ of periodic sinusoidal tapered section 222.

[0030] Process 400 then proceeds to step 406 where process 400 determines a width $W(x)$ of each point along a longitudinal distance of the periodic sinusoidal tapered section 222 based on the width W_{WG} of the straight section, the maximum width W_{MAX} and the minimum width W_{MIN} of the periodic sinusoidal tapered section as obtained from step 404. In particular, the width $W(x)$ of each position x along the longitudinal distance of the periodic sinusoidal tapered section may be defined as:

$$W(x) = (W_{WG} + \frac{W_{max} - W_{min}}{2}) \cos(2\pi x) + \frac{W_{max} + W_{min}}{2} | \cos(2\pi x) |$$

where x is a position along the longitudinal distance of the periodic sinusoidal tapered section.

[0031] Process 400 then proceeds to step 408. At this step, process 400 will determine the optimal values for W_{MAX} , W_{MIN} , W_{WG} , $W(x)$ and optimum period $\Lambda_{Optimum}$ of the periodic sinusoidal tapered section 222. These optimal values are determined as the iterations of these parameters that allow the waveguide to produce the largest main to highest side lobe ratio of an operating wavelength of the optical signal and the smallest angular difference between main lobes of the first wavelength λ_1 and the second wavelength λ_2 that are associated with the optical signal. Process 400 then utilizes these optimal values for the design of the waveguide.

[0032] In particular, to obtain the optimal values for the parameters mentioned above, the process 400 will first compute an initial period Λ_0 of the periodic sinusoidal tapered section. The initial period Λ_0 may be defined as:

$$\Lambda_0 = q_1 \frac{\lambda_1}{\Delta n_{eff,integ}} - q_2 \frac{\lambda_2}{\Delta n_{eff,integ}}$$

where q_1 is the high order diffraction of the first wavelength λ_1 , q_2 is the high order diffraction of the second wavelength λ_2 , $\Delta n_{eff,integ}$ is the effective index difference across all N parts of the period Λ_0 of the periodic sinusoidal tapered section. $\Delta n_{eff,integ}$ may be defined as:

$$\Delta n_{eff,integ} = \frac{1}{N} \sum_{j=1}^N |n_{eff,\lambda_1}(x_j) - n_{eff,\lambda_2}(x_j)|$$

where $n_{eff,\lambda_1}(x_j)$ is an effective index of the first wavelength λ_1 at part x_j of the N parts of the period Λ_0 of the periodic sinusoidal tapered section and $n_{eff,\lambda_2}(x_j)$ is an effective index of the second wavelength λ_2 at part x_j of the N parts of the period Λ_0 of the periodic sinusoidal tapered section.

[0033] Once process 400 has obtained the initial period Λ_0 of the periodic sinusoidal tapered section, process 400 then varies the initial period Λ_0 in a numerical simulation, within a range between $0.8\Lambda_0$ and $1.2\Lambda_0$, based on the width $W(x)$, the width W_{WG} , the minimum width W_{MIN} and the maximum width W_{MAX} as obtained in steps 404 and 406 until a variation of the initial period Λ_0 (i.e., a value between $0.8\Lambda_0$ and $1.2\Lambda_0$) that produces the best or the optimum far field projection of the waveguide antenna (based on these set of parameters) is obtained. In embodiments of this disclosure, the numerical simulation may comprise a finite-difference time-domain (FDTD) method that is configured to simulate a far field projection pattern of a single waveguide antenna. The exact workings of the FDTD method are omitted for brevity in this disclosure as its detailed workings are known to one skilled in the art. In other embodiments of this disclosure, the numerical simulation may instead comprise a frequency domain method or a finite element method.

[0034] Process 400 then determines if this far field projection of the waveguide is associated with the largest main to highest side lobe ratio of an operating wavelength λ associated with the optical signal (i.e., main to highest side lobe ratio > 10) and a smallest angular difference

between main lobes of the first wavelength λ_1 and the second wavelength λ_2 is obtained (i.e., $< 2^\circ$).

[0035] If process 400 determines that these conditions are not met, process 400 will return to step 404 to select another value for the minimum width W_{MIN} of the periodic sinusoidal tapered section from sub-library 1 and another value for the maximum width W_{MAX} of the periodic sinusoidal tapered section from sub-library 2, along with their associated effective refractive indexes. Process 400 may also assign another value to the width W_{WG} of the straight section and a larger value to N parts of period Λ of periodic sinusoidal tapered section 222.

[0036] Process 400 then recursively repeats steps 406 - 408 until it is able to obtain iterations of the maximum width W_{MAX} , the minimum width W_{MIN} , the width W_{WG} , the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section and the period Λ of the periodic sinusoidal tapered section that can produce a far field projection of the waveguide that can generate a sufficiently large main to highest side lobe ratio of an operating wavelength associated with the optical signal (i.e., main to highest side lobe ratio > 10) and a sufficiently small angular difference between main lobes of the first wavelength λ_1 and the second wavelength λ_2 is obtained (i.e., $< 2^\circ$). These values are then determined to be the optimal values for W_{MAX} , W_{MIN} , W_{WG} , $W(x)$ and optimum period Λ_{Optimum} of the periodic sinusoidal tapered section 222. Process 400 then ends.

[0037] In an embodiment of the disclosure, dual-mode waveguide antenna 200 may comprise waveguide 210 formed from 400nm thick Aluminum Nitride (AlN). In other embodiments, waveguide 210 may comprise silicon nitride (SiN) or any other materials that are transparent at the red, green and blue wavelengths, and the thickness of this material may be between 80nm and 800nm. As for cladding 205, this cladding may comprise Silicon Dioxide (SiO₂), and may comprise a substrate comprising Silicon Dioxide (SiO₂) and a superstrate comprising SiO₂. In this embodiment, the optimal values for the parameters above may be determined by process 400 as $W_{\text{MAX}} = 650\text{nm}$, $W_{\text{MIN}} = 400\text{nm}$, $W_{\text{WG}} = 500\text{nm}$, and the optimum period $\Lambda_{\text{Optimum}} = 3.124\mu\text{m}$, for an optical signal having a first wavelength λ_1 of 532nm and for an optical signal having a second wavelength λ_2 of 633nm, with high order diffractions $q_1 = 5$ and $q_2 = 4$.

Simulation Results

[0038] To simulate the performance of the dual-mode waveguide antenna designed in accordance with the steps set out in the previous section, a Finite-difference time-domain (FDTD) method was used to numerically study the far field projection pattern of a single dual-mode waveguide antenna. As only a single antenna was simulated, the beam projected to the far field varies only in θ while the other direction (ϕ) may be steered by varying the operating wavelength of the received optical signal.

[0039] Figure 5 illustrates the far field diffraction pattern 510 of a periodic sinusoidal tapered section of a dual-mode waveguide antenna when an optical signal having an operating wavelength λ_2 of 633nm is received. The periodic sinusoidal tapered section of the dual-mode waveguide antenna has the structural specifications of the embodiment mentioned in the previous section, for which the top-view schematic 505 is shown above projection pattern 510. From the simulation, it was found that a main beam appeared at an emission angle θ of 63.70° and that another order of diffraction was observed to the left of the main beam. Further, the simulation showed that the main to highest side lobe ratio was 10.1 for an operating wavelength λ_2 of 633nm.

[0040] Figure 6 illustrates the far field diffraction pattern 610 of a periodic sinusoidal tapered section of a dual-mode waveguide antenna when an optical signal having an operating wavelength λ_1 of 532nm is received. The periodic sinusoidal tapered section of the dual-mode waveguide antenna has the structural specifications of the embodiment mentioned in the previous section, for which the top-view schematic 605 is shown above projection pattern 610. From the simulation, it was found that a main beam appeared at an emission angle θ of 62.93° and that the simulation showed that the main to highest side lobe ratio for the far field pattern was 38 for an operating wavelength λ_1 of 532nm. Hence, the angular difference between the main lobes of the two operating wavelengths λ_1 and λ_2 is 0.77°.

[0041] When the projections patterns 510 and 610 (as shown in Figures 5 and 6) are compared, it can be seen that the two operating wavelengths λ_1 and λ_2 form a beam at almost the same angle when the same periodic sinusoidal tapered section of a dual-mode waveguide

antenna is utilized to receive and beam the optical signal. Additionally, it can also be seen that the projected side lobes that correspond to unwanted diffractions are effectively suppressed.

[0042] Figure 7 illustrates the far field pattern 710 of a tapered section of a dual-mode waveguide antenna with a periodic step profile when an optical signal having an operating wavelength λ_1 of 532nm was received. The waveguide antenna shown in Figure 7, for which the top-view schematic 705 is shown above projection pattern 710, has almost the same structural specifications of the embodiment mentioned in the previous section except that the N parts of the periodic sinusoidal profile is much coarser, i.e., $N=6$ instead of $N=100$ and the period Λ of the periodic stepped tapered section has been optimized based on the coarser N value. As a result, the profile of the tapered section resembles a periodic multi-step function instead of a smooth periodic sinusoidal profile. From the simulation, it was found that the waveguide antenna having the periodic stepped tapered section generated a main beam lobe at an emission angle θ of 63.35° and generated many unwanted side lobes 715 throughout the far field spectrum, when an optical signal having an operating wavelength λ_1 of 532nm was received.

[0043] Hence, when the far field patterns in Figures 6 and 7 are compared, it can be concluded that the slow sinusoidal change of the waveguide width enables better clearing of unwanted side lobes than the square step function. This shows that when finer steps are used to define the width profile of the waveguide along the longitudinal axis of the waveguide, i.e., the x-axis, the resulting transition from the minimum width W_{MIN} to maximum width W_{MAX} is smoother, and as a result, diffraction of the optical beam occurs in a more controlled manner as it propagates through the waveguide.

[0044] Figure 8 illustrates plot 805 which shows the normalized power remaining in the waveguide antenna after the optical signal has propagated $50\mu m$ along the longitudinal axis of the waveguide, i.e., the x-axis (with the power injected at the beginning of the waveguide being assigned a nominal value of 1.0). Because loss in the waveguide is mainly attributed to the symmetric up (+z) and down (-z) emission, the power level in the waveguide antenna at a certain distance away from the point of injection can be used to calculate the antenna's power emission rate.

[0045] As shown in plot 805, it can be seen that the normalized power level for two optical signals that have operating wavelengths $\lambda_1 = 532$ nm and $\lambda_2 = 633$ nm respectively are almost the same (< 1% difference), which indicates that the power emission rates for beam forming are also similar. Such a property enables color mixing to be realized easily, where optical beams of the right individual amounts are mixed to deliver the desired combination. When the different optical beams yield similar power levels from the major beam-forming device, power tuning can be made simpler and as a result, the system as a whole becomes more resistant to error and environmental disturbances.

[0046] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations, and modifications as falling within the scope of the appended claims.

CLAIMS:

1. A dual-mode waveguide antenna comprising:
 - a straight section configured to receive an optical signal;
 - a periodic sinusoidal tapered section optically coupled to the straight section, the periodic sinusoidal tapered section being configured to project the optical signal into an optical beam,
 - whereby a period Λ of the periodic sinusoidal tapered section is longer than an operating wavelength λ of the optical signal,
 - whereby a width W_{WG} of the straight section is smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and
 - whereby a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is equal to the width W_{WG} of the straight section.
2. The dual-mode waveguide antenna according to claim 1 whereby a width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section is determined based on the width W_{WG} of the straight section, the maximum width W_{MAX} and the minimum width W_{MIN} of the periodic sinusoidal tapered section.
3. The dual-mode waveguide antenna according to claim 2 whereby the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section is defined as:

$$W(x) = (W_{WG} + \frac{W_{max} - W_{min}}{2}) \cos(2\pi x) + \frac{W_{max} + W_{min}}{2} | \cos(2\pi x) |$$

where x is a position along the longitudinal distance of the periodic sinusoidal tapered section, W_{WG} is the width of the straight section, W_{MAX} is the maximum width and W_{MIN} is the minimum width of the periodic sinusoidal tapered section.

4. The dual-mode waveguide antenna according to claim 2 wherein optimal parameters for the maximum width W_{MAX} , the minimum width W_{MIN} , the width W_{WG} , the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section and period Λ of the periodic sinusoidal tapered section are determined based on iterations of these parameters that are able to produce a largest main to highest side lobe ratio of

the operating wavelength λ of the optical signal and a smallest angular difference between main lobes of a first wavelength λ_1 and a second wavelength λ_2 that are associated with the optical signal.

5. The dual-mode waveguide antenna according to claim 4 whereby the parameters for the maximum width W_{MAX} , the minimum width W_{MIN} and the width W_{WG} are recursively generated in each iteration.
6. The dual-mode waveguide antenna according to claim 5 whereby the period Λ of the periodic sinusoidal tapered section is determined by obtaining an initial period Λ_0 of the periodic sinusoidal tapered section and by varying the initial period Λ_0 in a numerical simulation of a far field projection of the dual-mode waveguide antenna based on the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section, the width W_{WG} , the minimum width W_{MIN} and the maximum width W_{MAX} until a variation of the initial period Λ_0 that produces an optimum far field projection of the dual-mode waveguide antenna is determined.
7. The dual-mode waveguide antenna according to claim 6 whereby an initial period Λ_0 of the periodic sinusoidal tapered section is determined based on the first wavelength λ_1 and the second wavelength λ_2 , a high order diffraction q_1 of the first wavelength λ_1 , a high order diffraction q_2 of the second wavelength λ_2 , and an effective index difference $\Delta n_{eff,integ}$ across all N parts of the period Λ of the periodic sinusoidal tapered section.
8. The dual-mode waveguide antenna according to claim 7, wherein the effective index difference $\Delta n_{eff,integ}$ across all N parts of the period Λ of the periodic sinusoidal tapered section is defined as:

$$\Delta n_{eff,integ} = \frac{1}{N} \sum_{j=1}^N |n_{eff,\lambda_1}(x_j) - n_{eff,\lambda_2}(x_j)|$$

where $n_{eff,\lambda_1}(x_j)$ is an effective index of the first wavelength λ_1 at part x_j of the N parts of the period Λ of the periodic sinusoidal tapered section and $n_{eff,\lambda_2}(x_j)$ is an

effective index of the second wavelength λ_2 at part x_j of the N parts of the period Λ of the periodic sinusoidal tapered section.

9. The dual-mode waveguide antenna according to claim 8, wherein the initial period Λ_0 of the periodic sinusoidal tapered section is defined as:

$$\Lambda_0 = q_1 \frac{\lambda_1}{\Delta n_{eff,integ}} - q_2 \frac{\lambda_2}{\Delta n_{eff,integ}}$$

where q_1 is the high order diffraction of the first wavelength λ_1 , and q_2 is the high order diffraction of the second wavelength λ_2 .

10. The dual-module waveguide antenna according to claim 1 whereby the straight section and the periodic sinusoidal tapered section comprises Aluminum Nitride (AlN) formed on a Silicon Dioxide (SiO₂) substrate and cladded in a Silicon Dioxide (SiO₂) superstrate.

11. A method of forming a dual-waveguide antenna, the method comprising:

forming a straight section of the dual-waveguide antenna, the straight section being configured to receive an optical signal;

forming a periodic sinusoidal tapered section of the dual-waveguide antenna such that the periodic sinusoidal tapered section is optically coupled to the straight section, the periodic sinusoidal tapered section being configured to project the optical signal into an optical beam,

whereby a period Λ of the periodic sinusoidal tapered section is formed such that the period Λ is longer than an operating wavelength λ of the optical signal,

whereby a width W_{WG} of the straight section is formed such that the width W_{WG} is smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and

whereby a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is formed such that the width at the midpoint of each period Λ is equal to the width W_{WG} of the straight section.

12. The method according to claim 11, further comprising the step of determining a width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section based on

the width W_{WG} of the straight section, the maximum width W_{MAX} and the minimum width W_{MIN} of the periodic sinusoidal tapered section.

13. The method according to claim 11 whereby the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section is defined as:

$$W(x) = (W_{WG} + \frac{W_{max} - W_{min}}{2}) \cos(2\pi x) + \frac{W_{max} + W_{min}}{2} |\cos(2\pi x)|$$

where x is a position along the longitudinal distance of the periodic sinusoidal tapered section, W_{WG} is the width of the straight section, W_{MAX} is the maximum width and W_{MIN} is the minimum width of the periodic sinusoidal tapered section.

14. The method according to claim 12 wherein optimal parameters for the maximum width W_{MAX} , the minimum width W_{MIN} , the width W_{WG} , the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section and period Λ of the periodic sinusoidal tapered section are determined based on iterations of these parameters that are able to produce a largest main to highest side lobe ratio of the operating wavelength λ of the optical signal and a smallest angular difference between main lobes of a first wavelength λ_1 and a second wavelength λ_2 that are associated with the optical signal.

15. The method according to claim 14 further comprising the step of recursively generating the parameters for the maximum width W_{MAX} , the minimum width W_{MIN} and the width W_{WG} in each iteration.

16. The method according to claim 15 whereby the period Λ of the periodic sinusoidal tapered section is determined by obtaining an initial period Λ_0 of the periodic sinusoidal tapered section and by varying the initial period Λ_0 in a numerical simulation of a far field projection of the dual-mode waveguide antenna based on the width $W(x)$ along a longitudinal distance of the periodic sinusoidal tapered section, the width W_{WG} , the minimum width W_{MIN} and the maximum width W_{MAX} until a variation of the initial period Λ_0 that produces an optimum far field projection of the dual-mode waveguide antenna is obtained.

17. The method according to claim 16 whereby an initial period Λ_0 of the periodic sinusoidal tapered section is determined based on the first wavelength λ_1 and the second wavelength λ_2 , a high order diffraction q_1 of the first wavelength λ_1 , a high order diffraction q_2 of the second wavelength λ_2 , and an effective index difference $\Delta n_{eff,integ}$ across all N parts of the period Λ of the periodic sinusoidal tapered section.

18. The method according to claim 17, wherein the effective index difference $\Delta n_{eff,integ}$ across all N parts of the period Λ of the periodic sinusoidal tapered section is defined as:

$$\Delta n_{eff,integ} = \frac{1}{N} \sum_{j=1}^N |n_{eff,\lambda_1}(x_j) - n_{eff,\lambda_2}(x_j)|$$

where $n_{eff,\lambda_1}(x_j)$ is an effective index of the first wavelength λ_1 at part x_j of the N parts of the period Λ of the periodic sinusoidal tapered section and $n_{eff,\lambda_2}(x_j)$ is an effective index of the second wavelength λ_2 at part x_j of the N parts of the period Λ of the periodic sinusoidal tapered section.

19. The method according to claim 18, wherein the initial period Λ_0 of the periodic sinusoidal tapered section is defined as:

$$\Lambda_0 = q_1 \frac{\lambda_1}{\Delta n_{eff,integ}} - q_2 \frac{\lambda_2}{\Delta n_{eff,integ}}$$

where q_1 is the high order diffraction of the first wavelength λ_1 , and q_2 is the high order diffraction of the second wavelength λ_2 .

20. An optical phased array system comprising:

a plurality of dual-mode waveguide antennas,

whereby each dual-mode waveguide antenna comprises:

a straight section configured to receive an optical signal;

a periodic sinusoidal tapered section optically coupled to the straight section, the periodic sinusoidal tapered section being configured to project the optical signal into an optical beam,

whereby a period Λ of the periodic sinusoidal tapered section is longer than an operating wavelength λ of the optical signal,

whereby a width W_{WG} of the straight section is smaller than a maximum width W_{MAX} of the periodic sinusoidal tapered section and larger than a minimum width W_{MIN} of the periodic sinusoidal tapered section, and

whereby a width at a midpoint of each period Λ of the periodic sinusoidal tapered section is equal to the width W_{WG} of the straight section.