Novel Blue-green Light Phased Array by Light-sheet-excited One-dimension Strip Grating Array

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Abstract: We demonstrate a novel blue-green light phased array by light-sheet-excited 1D strip waveguide grating with nearly spot emission profile. By tuning wavelength, the range 15° of beam steering was achieved.

1. Introduction

Integrated Optical phased array (OPA) enables very stable, rapid and precise beams steering without mechanic motion, making them robust and insensitive to external constrains such as acceleration, which have an attractive application in the fields of LiDAR and free-space optical communications [1,2]. Practical implementations of integrated optical phased arrays for above applications requires large optical apertures to realize a small divergence angle and provide a large receiving area [3]. The traditional one-dimensional optical phased array is formed by integrated single-mode waveguide on silicon-on-insulator, thus it can achieve large apertures since their length of waveguide may reach millimeter scale [4]. The beam steering principle of OPAs is the same as that of microwave arrays, where a beam direction is controlled by tuning the phase relationship between the arrays of silicon-based waveguide [5]. However, in the designing of blue-green OPAs for underwater wireless optical communication (UWOC), the total loss including outcoupling loss of OPA, fiber-to-OPA efficiency and propagation loss in the sub-micrometer waveguide is too high for short wavelengths of 450-550 nm, which significantly decreases the underwater communication distance and capacity [6].

In this paper, we report a 1D blue-green OPA on silicon nitride strip waveguide by light sheet excitation on the side of waveguide array, realizing the beams steering upon the waveguide array direction by wavelength-tuning. Benefiting from the interference of scattering light from the periodic waveguides structure of OPA, the transmitting efficiency of optical far field from the waveguide array is much higher than the emitting light from the end of waveguide array because of higher coupling efficiency. It's noted that the main-lobe from the common 1D waveguide OPA is not line type but nearly spot distribution like the 2D waveguide OPA acts [7], which is caused by interference of scattering light rather the transmitting light from the end of waveguide array. Furthermore, the beams steering of such 1D waveguide OPA can be realized by wavelength tuning rather than phase control by complex electro-optic modulation structure. In the designed and fabricated blue-green OPA based on SiNx technology, the grating optical antenna area is combined of 64 channel waveguides with spacing of 1.5 μm with the length of 105 μm, which consists of a large and square antenna area. This design predicts the 15° steering angle in the range of blue-green bandwidth and 0.3° angle resolution. Thereby, just based on traditional 1D waveguide OPA, we can increase its emitting efficiency and realize the beams steering of wavelength tuning by light sheet excitation on the side of waveguide array. This work will greatly optimize the function of blue-green OPA and promote its application in UWOC.

2. OPA Design and Methodology

We take the strip waveguide grating as the OPA aperture to achieve large antenna area for interference light emitting. Since the end radiation of waveguide array in the near field can provide the narrow and long illumination area, another uniform waveguide grating is employed for implementing the special light sheet illumination on the side of above OPA, which the two strip waveguide gratings have same square shape and size to guarantee the light coupling efficiency. The OPA presented in this work were fabricated based on SiNx foundry technique as reported in [8]. Figure 1(a) illustrates the schematic diagram of the proposed OPA layout by the novel light sheet excitation. The first OPA consists of an edge coupler with inverse taper design, 6 stages of 1×2 multimode interference (MMI) splitter trees and 64 channels of silicon nitride strip waveguide grating arrays. The waveguide direction of second OPA is vertical to that of first one and is about 100 μm away from the first OPA to satisfy the light sheet excitation. Here it's noted that by taking the side coupling for OPA2, it can provide the quasi-spot far field and realize the beams steering by wavelength-tuning in the direction of waveguide grating array. The thickness of each waveguide in the OPA antenna is 300 nm with its width and length are 0.55 μm and 105 μm separately, and the waveguide spacing d is 1.5 μm. The

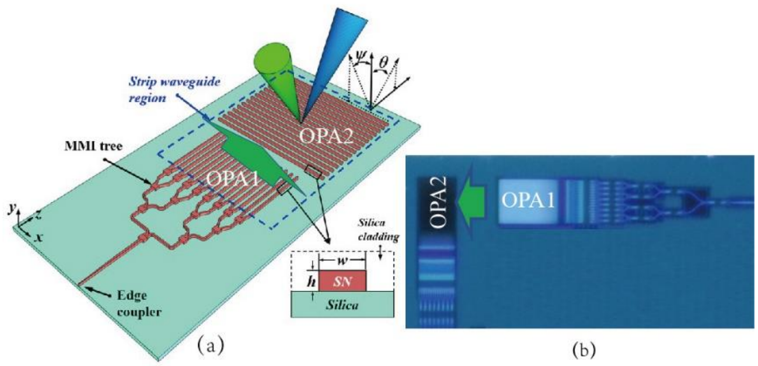

Fig. 1. (a) Schematic diagram of the proposed OPA beam steering platform by the novel light sheet excitation; (b) Microscopic top-view of the proposed OPA layouts in experiment.

two waveguide arrays have the same structure parameter. Fig. 1(b) shows the top-view of the two fabricated OPAs, where one is for light illumination and the other is for emitting far field of interference light from the waveguide array.

In order to realize the narrow and long coupling area to the side of waveguide array, the two OPAs is fabricated in the same silicon nitride layer, and the cladding around the waveguide is silicon dioxide. The two fabricated OPAs in the same layer with spacing of 100 μm to make the emitting light from OPA1 to mostly confine in the waveguide layer to get high coupling efficiency into OPA2. The far field analysis from OPA2 under the wavelength tuning is simulated by the commercial software Lumerical FDTD solutions, and the optical field distribution coupling into OPA2 is assumed in a long rectangle area with uniform intensity. The projected far-field radiation from OPA2 is polarization-insensitive since its interference formed by scattering light from the strip waveguide is non-polarized dependent, which is different from polarization dependent OPA as previously reported in [9, 10]. For comparison, the far fields of end radiation and scattering from the strip waveguide array are firstly analyzed. After that, the beams steering by wavelength tuning in green light of selected 506nm, 518nm, and 523nm are both predicted by simulation and demonstrated by experiments. In our experiments, a single-mode optical fiber is adopted to couple the laser to the OPA1 firstly and then most of the light propagating through the OPA1 is coupled into OPA2.

3. Results and Discussion

The emitting light properties from the proposed OPAs including deflection, divergence angles and the beams steering characteristics are investigated. Fig. 2(a) and 2(b) shows the simulation far fields from strip waveguide array of OPA2 by MMI coupling and light sheet coupling respectively at the wavelength of 518nm. It can be seen that the grating lobes are distributed along the waveguide array direction ψ with the intensity distribution being line type as typical 1D grating OPA acts. The position of 2nd order grating lobes can be calculated by the equation: $\psi'=\pm sin^{-1}(\lambda/d)$, where is about ±20° shown in the Fig. 1(a). For the situation of light sheet coupling in figure 1(b), the intensity profile is nearly spot pattern and the grating lobes are also distributed in the waveguide array direction. The special far field pattern by the strip waveguide array is because of the interference of scattering light from the side of each waveguide, which is similar like the Fraunhofer diffraction with light being incident on a rectangular hole. And the 2nd side lobe has the same deflection angle ±20° compared to main-lobe in waveguide array direction since the same waveguide period. Figure 1(c) shows the experimental far field from OPA2 at the wavelength of 518nm, it can be seen that it’s consistent with the simulation result.

We numerically and experimentally investigate the beams steering characteristic by wavelength tuning. Figure 2(d) and 2(e) show the measured spectrum and the multi-wavelength main lobes in experiment with wavelength of 506 nm, 518 nm, 523 nm multiplexing into the proposed OPA. It can be seen that distinguished from the common beams’ deflection by wavelength tuning along the longitudinal direction, here the spot patterns separate with each other along the waveguide array direction. It can avoid the light fields overlap of wavelength multiplexing in narrow bandwidth and has the great advantage for WDM wireless communication to moving object with high emitting efficiency, which has the more optimized optical field distribution than common 1D OPA, and higher emitting efficiency for traditional 2D OPA.

In addition, the beam divergence angle ψ_{FWHM} of the main lobes were measured as 0.32°, 0.33°, 0.35° for above three wavelengths of 506nm, 518nm, and 523nm. These values match very closely with simulation results of 0.29°, 0.31°, 0.32° by FDTD simulation. Furthermore, the steering angle of main lobe variation in the whole blue-green bandwidth

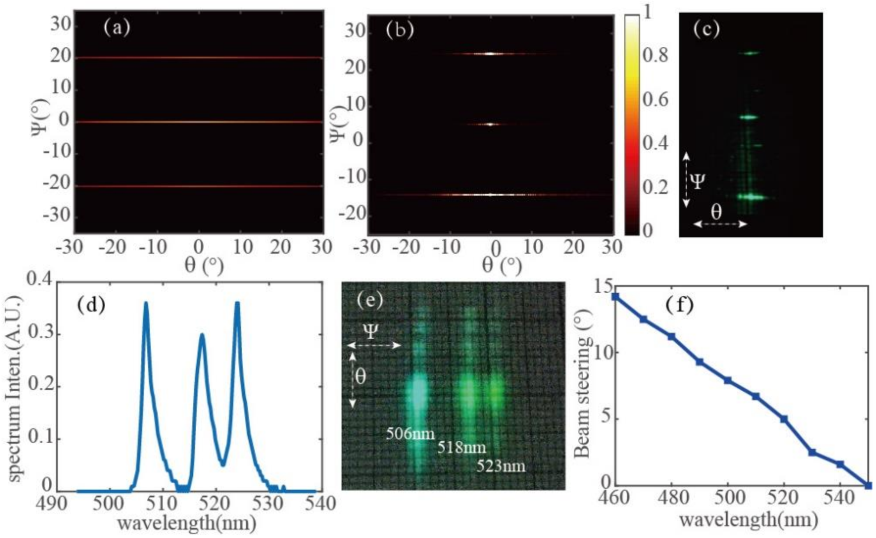

Fig. 2 The simulated far fields from strip waveguide array of OPA2 by (a) MMI coupling and (b) light sheet coupling at the wavelength of 518 nm; (c) the experimental far field from the waveguide array of OPA2 at the wavelength of 518 nm; (d) the measured spectrum and (e) multi-wavelength main lobes in experiment with wavelength of 506 nm, 518 nm, 523 nm multiplexing into the proposed OPA; (f) the steering angle of main lobe versus blue-green wavelength.

has been analyzed shown in figure (f). It can be seen that the deflection angle of main-lobe linearly varies with the light wavelength along the waveguide array direction. And the beams steering range can reach to 15° by wavelength tuning in such visible light bandwidth.

4. Conclusion

In conclusion, we propose a new scheme of OPA by light sheet excitation based on traditional strip waveguide array to get high-efficiency light emitting with nearly spot intensity profile, and also realize the beams steering by wavelength tuning in the special waveguide array direction. Our experimental and simulation results show that such kind of OPA that designed in the blue-green wavelengths has high far-field efficiency as the 1D OPA acts, meanwhile the beams deflection angle can reach to 15° in this visible light range.

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