Multiple-Output and Arbitrary Power-Ratio Beam Splitter on Dielectric Metasurface

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***Abstract*—We demonstrate a multiple-output and arbitrary power-ratio beam splitter on all-dielectric metasurface. An illustrative 5-output beam splitter is prepared and measured manifesting high beam-splitting ratio fidelity and broadband performance, which is promising for multi-beam applications.**

Keywords—metasurface, beam splitter, arbitrary power ratio, phase pattern

I. Introduction

The optical beam splitter (BS) is a key component for distributing the light path in the photonic system. In free-space optical system, traditional transflective BS with bulky size is still the most mainstream scheme [1]. In recent years, several works have demonstrated planar BSs, such as plate BS [2], dichroic BSs [3] and metasurface-empowered BSs. Among them, metasurfaces, which can arbitrarily manipulate the amplitude [4], phase [5], polarization [6] of light, have become an emerging option for BSs. For example, plasmonic encoding metasurfaces in microwave band [7], binary metasurface [8] and meta-gratings in visible light [9] have been reported. There is also a correponding report in near-infrared [10], using silicon-based dielectric metasurface to construct BS with tunable power ratio. The above-mentioned free-space BSs have to face many limitations since the adjustment of splitting ratio depends on the frequency or polarization discrepancy or the tunable substrate refractive index. On the other hand, encoded metasurfaces with topological optimization or inverse design require high-cost computational process.

Here, we proposed and demonstrated a multiple-output and arbitrary power-ratio BS. A generic and straightforward optimization algorithm has been utilized to optimize a phase-only pattern for accurate amplitude-phase modulations. After that, an all dielectric metasurface has been implemented to load such optimized phase pattern. As a proof of concept, an illustrative 5-output BS example has been prepared and measured. The experimental total splitting efficiency (*TSE*) is above 62% and the beam-splitting ratio fidelity (*SRF*) is above 0.997. We hold the envision that such multi-beam controllability and power dividing are promising to apply in many fields such as phase controlled electronically scanned array radar (PCESAR) systems, multiple-input multiple-output (MIMO) communication [11] and optical computing systems [12].

II. Design Methodology And Fabrication

The design is to construct a complex phase pattern that can split the single-wavelength and single-polarization incident light into distinct outgoing orientations. Although superimposed Bragg grating can deflect the incident beam to multiple directions simultaneously [13], nonuniform power ratio cannot be satisfied. We consider the phase of a composed Bragg grating with respective amplitude ratio as an original phase (formulized by equation 1), and then a gradient-descent optimization algorithm is further employed so that the iterated optimized phase pattern can perform more accurate and non-uniform beam splitting. The principle of the algorithm is briefly depicted that the minimum value of the loss function is iteratively searched along the gradient direction by means of optimizing the complex variables. Fig. 1(a) exhibits an optimized phase pattern example of a BS with power ratio of 1:2:3:4:5. After that, we apply this optimized phase pattern to construct a metasurface-based BS device, which is comprised of an array of Si nanopillars. The construction process is separated into two steps. Firstly, through sweeping and selecting proper parameters at 1550nm operating wavelength, a "Si meta-atoms library", which covers 0~2π phase retardance and high transmittance, can be established (shown in Fig. 1(b)). After obtaining the mapping relation between the radius of Si nanopillars and the phase retardance, the second step is to deduce the radius pattern of Si nanopillars combined with the aforementioned optimized phase pattern. Fig. 1(c) exhibits the Si-nanopillar radius pattern of the metasurface-based BS with power ratio of 1:2:3:4:5.

$$P_{original}(\boldsymbol{r}) = \arg\{\sum_{n=1}^{N} A_n \exp\left[-i\boldsymbol{k}_n \cdot \left(\boldsymbol{r} - \boldsymbol{R}_n\right)\right]\} \qquad (1)$$

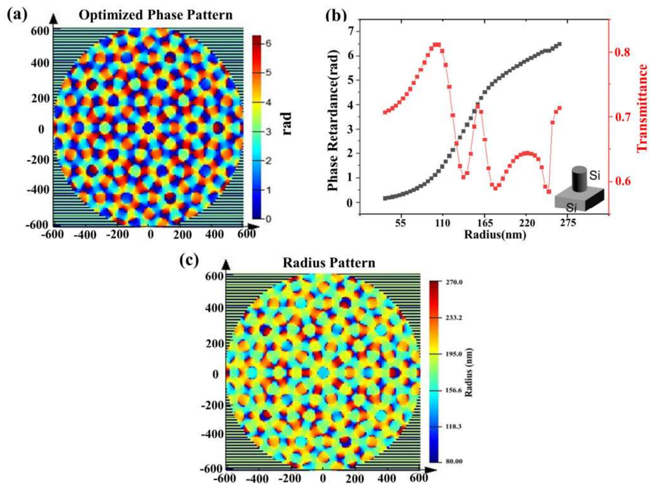

Fig. 1. The design methods of the proposed multiple-output and arbitrary power-ratio BS. (a) The optimized phase pattern of a BS with power ratio of 1:2:3:4:5. (b) The established "Si meta-atoms library" which covers 0~2π phase retardance and high transmittance. (c) The radius pattern of Si nanopillars of the BS with power ratio of 1:2:3:4:5.

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Further, we have simulated the output of the constructed metasurface-based BS *via* finite difference time domain (FDTD) method. On the transverse plane, the spatial distribution of the output sub-beams is designed as a circular pattern formed by individual beam spots. The incident light is set as fundamental Gaussian mode and *x*-direction polarization at wavelength of 1550nm. The simulated beam-splitting result is shown in Fig. 2(a). Moreover, the extracted normalized intensity versus the azimuth angle θ of Fig. 2(a) is illustrated as Fig. 2(b), which is quite consistent with ideal power ratio.

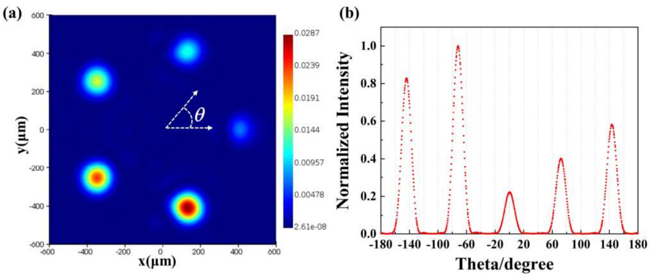

Fig. 2. The simulation verification of the BS with power ratio of 1:2:3:4:5. (a)The simulated beam-splitting result of the BS. (e) The extracted normalized intensity versus the azimuth angle θ.

In fabrication, the preparation scheme has been explored through combined micro-nano processing technology. Firstly, a 200nm-thick Au marker is prepared *via* electron beam (EB) evaporation, ultra-violet lithography and inductively coupled plasma reaction ion etching (ICP-RIE) process. Following this, the metasurface structure is fabricated by electron beam lithography (EBL) and reaction ion etching (RIE). Particularly, a two-layer hard mask of Cr and SiO_2 is utilized to increase the depth-to-width ratio. The process of metasurface preparation is shown in Fig. 3(a). The optical microscope and scanning electron microscope (SEM) images of the fabricated sample are shown in Fig. 3(b) and 3(c), respectively.

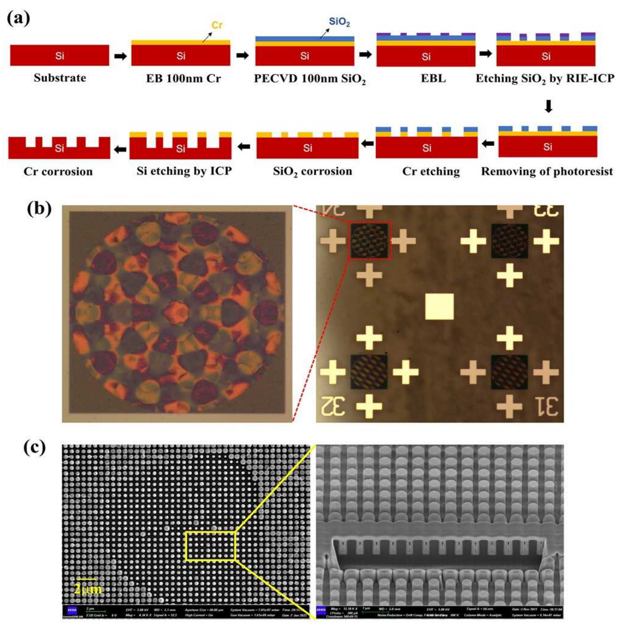

Fig. 3. The fabrication process and microscope images of the metasurface sample. (a) The flow diagram of fabrication process. (b) The optical microscope and SEM images of the fabricated sample.

III. Experiment Set-up And Results

Fig. 4 gives the sketch of experimental setup for beam splitting measurement. A tunable laser (SANTEC TSL-710) is adopted to characterize the broadband performance. After passing through a collimating and beam expanding system, the incident Gaussian-mode light is refocused on the metasurface sample bracket by a confocal system, and then captured by charge-coupled device (CCD, ARTCAM-0016TNIR). The confocal system comprised of a lens and an objective lens is specifically designed for chip location and alignment with incoming laser beam (the inset CCD image in Fig. 4).

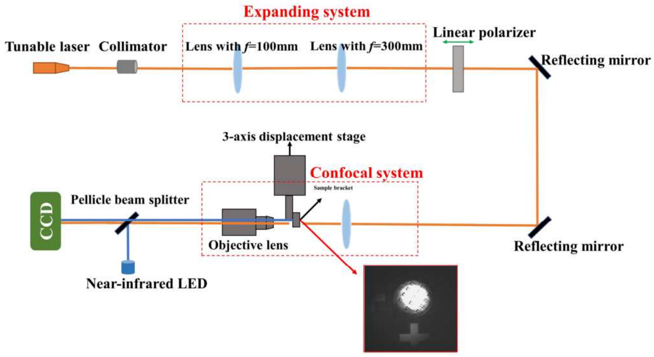

Fig. 4. The experimental setup for beam splitting measurement

The inset of Fig. 5(a) exhibits the captured CCD image at the designed operation wavelength of 1550nm. Fig. 5(a) also depicts the extracted normalized intensity versus the azimuth angle θ. To quantitatively measure the performance of the fabricated sample, two parameters are adopted. One is the total splitting efficiency (*TSE*), which is referred to as the desired splitting sub-beams dividing by the all transmitted light. The other is beam-splitting ratio fidelity (*SRF*), which is the normalized inner product of the theoretical splitting ratio vector and the experimental splitting ratio vector. The simulated and measured (calculated by the received optical power of CCD) *TSE* and *SRF* are summarized in Fig. 5(b) and 5(c), respectively. The difference of simulation and experiment is mainly attributed to the fabrication error and measurement deviation. The experimental results also reveals that operating bandwidth is more than 100nm.

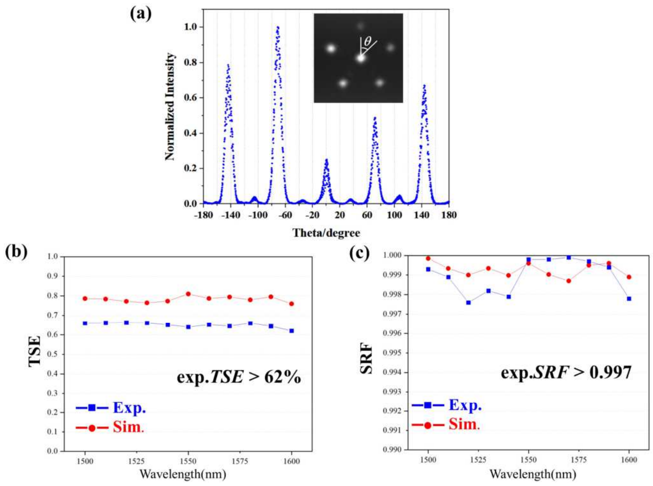

Fig. 5. The experimental results of the BS with power ratio of 1:2:3:4:5. (a) The experimental beam-splitting result of the BS. Inset: the image captured by CCD. (b) The experimental (blue squares) and simulated (red dots) *TSE* within 100nm wavelength coverage. (c)The experimental (blue squares) and simulated (red dots) *SRF* within 100nm wavelength coverage.

IV. Conclusion

In conclusion, by gradient-descent-based phase pattern optimization and all-dielectric metasurface, we have proposed and demonstrated a multiple-output and arbitrary power-ratio BS. Taking a concrete BS example with power ratio of 1:2:3:4:5 and circular arrangement of splitting sub-beams, above 62% *TSE* and above 0.997 beam-splitting fidelity have been achieved. It should be mentioned that the design methodology and preparation process are general for an arbitrary power-ratio and multiple-output BS. We believe that such multi-beam controllability and power dividing have great potential for applying in many optical fields.

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