Silicon-based star coupler power splitter with enhanced non-uniformity

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We designed and fabricated a SOI based insertion loss non-uniformity enhanced star coupler with improved total transmission. The design utilizes a 'squeeze' dual input taper with auxiliary input taper placed right next to the central input taper. The specially designed taper structure transforms the fundamental Gaussian-shaped input profile at the entry of the free propagation region into a sinc mode field which produces a flat-top far field profile at the output waveguides array, without adding to the overall device footprint.

1. Introduction

On-chip laser source on Silicon-on-Insulator (SOI) photonic platform remains a big challenge and the external integrated laser has weaker output power and modulation linearity compared with a commercial off-the-shelf package laser source. To reduce the number of laser sources for realizing large-scale multi-channel optical systems, efficiency and compact on-chip optical power splitter are needed, such as the optical phase array (OPA) based beam-steering device and the light detection and ranging system (LiDAR) [1].

So far, Mach-Zehnder Interferometer (MZI) based power splitting tree, directional coupler splitter tree and star coupler based on silicon-on-silica platform has been demonstrated. With the rapid development of the SOI technology, the power splitting unit and the splitter tree with very small footprint can be realized due to the high refractive index contrast of the silicon nanowire. However, the total device size using unit splitter tree is still large when large number of channels are needed. It also suffers from severe back-reflection and signal interference, which accumulate with the number of layers in the power splitter tree.

Star-coupler based power splitter emerged as an alternative to the power splitter tree. It can scale the output channel number without increasing the device footprint. However, convention star coupler designed for array waveguide gratings (AWGs) suffer from high channel loss non-uniformity, which is defined as the transmission difference between the output channel situated in the center and the edge [2]. The power profile of light when it reaches the output waveguide array has a quasi-Gaussian shape, therefore, the channel on the edge has a higher power loss compared with the channel on the center. There is a large trade-off between the total device insertion loss and loss non-uniformity. Auxiliary waveguides have been introduced to generate a sinc-shape power profile at the input of the free propagation region on both SOI and Silica platform [3]. Xia et al. reduces the loss non-uniformity by twisting the input waveguide angle at the free propagation region (FPR) interference and flatten the power distribution at the output [4]. Wave Front Matching (WFM) method has been used to design input array waveguide to enhance the directional coupling between the main and auxiliary waveguide to generate better sinc-profile at the FPR entry [5]. However, the research mentioned above is design for AWG demultiplexers which focuses on the transmission spectra non-uniformity [6, 7, 8, 9, 10].

In this paper, we introduce an SOI-based star coupler power splitter with improved loss non-uniformity by using auxiliary tapers with a 'squeezed' dual taper input. The footprint of star coupler power splitter is only 25×25μm and the design is easy to fabricate with high fabrication error tolerance.

2. Theory and Simulation

The star coupler power splitter can be divided into three sections: The input directional coupling taper/waveguide array, the free propagation region (FPR), and the output waveguide array. The input directional coupling taper array generates a sinc-function shape power profile at the entry of FPR, of which the Fourier transformation is a rectangular function, and it gives a flat-top far field power distribution. When light enters the FPR, the beam profile previously confined in the taper starts to expand freely. The beam divergence angle can be calculated as

$$\theta_{diverge} = M^2 \frac{\lambda}{\pi w_0}. \quad (1)$$

Where θ is the beam divergence angle, M^2 represents the beam quality factor, λ represent the wavelength of light and w_0 represent the beam profile radius. For the sinc-function shape light input, the beam profile radius is the half width half maximum (HWHM) of the main lobe of the light intensity distribution at the entry plane of the FPR.

The output waveguide array divides and collects the light beam power after it propagates through the FPR. Since aberration-free output configuration is not required for a pure power splitter, the output array does not need to be mounted in a Rowland circle. The output waveguide array will be placed along the wavefront of the free propagating beam instead so that the light collected by the output waveguides is phase matched.

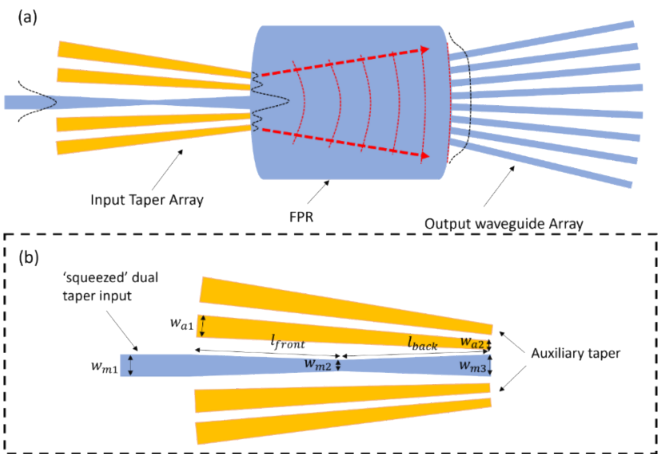

Fig. 1. Schematics of (a) the non-uniformity enhanced star coupler power splitter and (b) the input taper array with 'squeezed' dual taper input.

For a traditional star coupler designed for array waveguide grating (AWG), every array waveguide serves as an individual input, and the field distribution at the entry plane of the FPR can be approximated by a Gaussian distribution, which leads to a Gaussian envelope at the far field. As a result, the power loss at the output waveguide at the edge is larger than the output waveguide placed in the center. In our star coupler power splitter design, the auxiliary taper is introduced for directional coupling and to obtain the desired sinc-function profile. In addition, the central taper is 'squeezed' in the middle to enhance the coupling with the neighboring array tapers. The designed structure of our star coupler input taper array is presented in Fig. 1(a). The output waveguide array is placed along the wavefront of the free propagating beam, as can be seen in Fig. 1(b).

The goal of the simulation is to optimize the parameter setting of the auxiliary and central 'squeezed' taper so that a flat-top far field can be obtained. The initial simulation region includes the input array taper and FPR. After a desired far-field profile is found. The output array waveguide is added to the simulation region for calculating the device insertion loss and the non-uniformity. 2.5D finite-difference-time-domain (FDTD) is used for accurate and efficient simulation. The parameter setting of the star coupler is given in Table 1.

Table 1. Design Parameters for the squeezed dual taper star coupler

Parameters	Value
Central wavelength [μm]	1.55
Starting Width of the Auxiliary Taper [nm]	500
Ending Width of the Auxiliary Taper [nm]	450
Length of the auxiliary Taper [μm]	14
Half-length of the squeezed central waveguide [μm]	7

A laser source with the fundamental transverse electric mode (TE) is launched into the central waveguide. To simplify the optimization of the input array, the gap between input tapers is set to be 0.1μm. The width of the input end w_a1 and the output end w_{a2} of the auxiliary taper set to be 0.5 μm and 0.45 μm respectively. The width of the main taper output is set to 525 nm, with which the theoretical divergence angle of laser beam is 30 degrees. The range of w_{m1} is increased from 0.45 μm to 0.6 μm and w_{m2} is sweep from 0.25 μm to 0.45 μm.The length of the front and back side of the taper is set to be $l_{front} = l_{back} = 7mm$ After sweeping the parameters, the far field power distribution of the input taper array is obtained and the standard deviation of optical power within the beam divergence angle is calculated. Fig. 2(a) shows the result of the star coupler optimization based on the standard deviation of the far-field coupling efficiency within the beam divergence angle. Four optimal solutions are being selected for further analysis.

Fig.2 (b) shows the power distribution of transverse beam profile as light enters the FPR for conventional and optimized solution. Compared with traditional power splitting star coupler design, our design shows reduced device insertion loss and non-uniformity. As can be seen in Fig. 2(c), the power oscillation of far-field power distribution within the beam divergence angle is reduced, after replacing the conventional single taper input with dual-taper input paired with auxiliary taper.

To have the optimal utilization of the expanded light beam power, the output waveguides need to be placed as closely as possible to avoid excessive back reflection from the waveguide gap wall. The length of FPR is set as 8 μm to ensure far field operation of the power splitter. The output waveguide width is set to be 550 nm, so that a total of 10 output waveguides can be accommodated within the theoretical beam divergence angle.

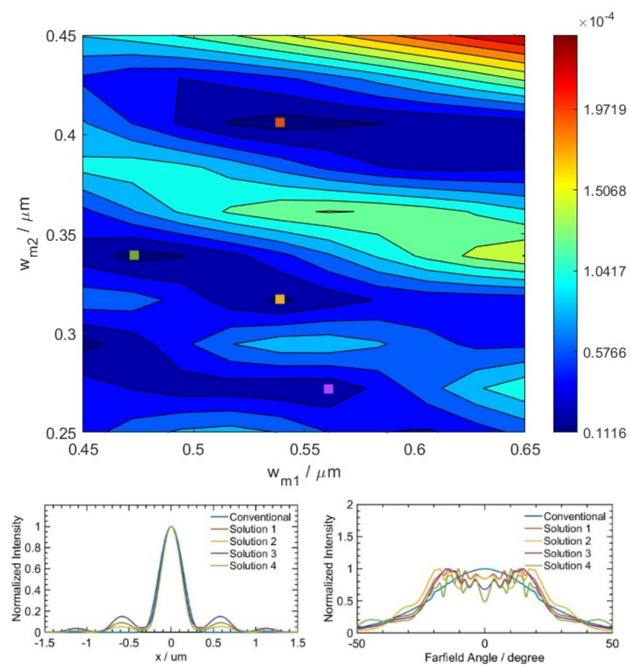

Fig. 2. Optimization for the 10-output channel star coupler. (a) contour plot of the power standard deviation. (b)FPR input profile and (c) far-field power distribution of conventional and non-uniformity improved star coupler design.

Fig. 3. shows the simulated channel transmission for the 10 output channels for conventional and the non-uniformity enhanced star coupler power splitter design. The best solution among the optimization results, solution 1, shows that the overall coupling efficiency to the central channels increased significantly from 49.07% to 62.53%. The coupling efficiency non-uniformity dropped from 1.0125 to 0.6407. Only the 10 channels in the middle are used for calculation of transmission and non-uniformity.

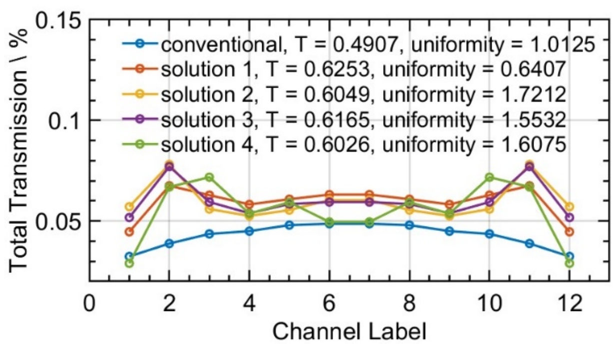

Fig. 3. Simulated total transmission and the non-uniformity for conventional and non-uniformity enhanced star coupler design.

For the fabrication of the device, a conventional and a non-uniformity enhanced star coupler design based on solution 1 has been made in a nanofabrication facility at SiPhotonIC Technologies. The devices were fabricated on a SOI platform with a 250 nm thick silicon layer epitaxially grown on a 3μm thick silicon substrate. The waveguide structures were defined by e-beam lithography (EBL) followed by inductively coupled plasma etching and e-beam resist stripping. Afterwards, a 1 μm thick layer of SiO2 is sputtered on top of the SOI layer, followed by chemical mechanical planarization (CMP) to smoothen the surface.

3. Conclusion

In conclusion, we have designed and fabricated a non-uniformity enhanced star coupler based on 'squeezed' dual taper and auxiliary input taper. The total coupling region length is 14 μm in length and 4 μm in width. The design transforms the fundamental Gaussian FPR input profile into a sinc power distribution, which results in a flat-top far-field power distribution. The total transmission and insertion loss non-uniformity is improved without adding extra photonic structure or increasing device footprint.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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