TuF1.3 (Contributed)
9:15 AM - 9:30 AM

Demonstration of a Tunable Broadband Coupler

Minh Tran, Jared Hulme, Sudharsanan Srinivasan, Jonathan Peters, John Bowers
Department of ECE, University of California, Santa Barbara, California, USA
Email: minhtran@ece.ucsb.edu

***Abstract*— We analyzed and fabricated a novel coupler which possesses wavelength flattened response and splitting ratio tuning capability. The fabricated coupler showed a flattened response to wavelength over 50 nm bandwidth and the coupling power to the cross port can be tuned from 10% to 70%.**

Keywords*— *tunable; broadband; coupler; silicon photonics

I. INTRODUCTION

An optical waveguide coupler is an essential component in photonic integrated circuits (PIC). The simplest structure is the directional coupler, which consists of two waveguides close to each other so that light can be coupled between the two waveguides [1]. The power splitting ratio, *i.e.* the ratio between the cross port and the total power, of this coupler is determined by the waveguide widths, the gap and the length of the coupling region and is very sensitive to fabrication errors. Consequently, it is difficult in practice to obtain a directional coupler with the exact power splitting ratio. Some applications, such as ring resonators or optical gyroscopes require splitting ratios very close to some value (50% for gyros to cancel the backscatter noise). A tunable directional coupler, which can be realized by exploiting the thermally induced phase velocity mismatch [2, 3], is sometimes necessary. However, the splitting ratio of the aforementioned coupler is extremely sensitive to the wavelength of light, especially in high contrast waveguides for silicon photonics [4]. Therefore, they are not suitable to many broadband light source based applications *e.g.* optical gyroscope, tomography or bio-sensing.

On the other hand, adiabatic couplers and a multimode interference (MMI) couplers [5] are less sensitive to wavelength and have larger tolerance to fabrication variations. However, the splitting ratios of these types are limited (*e.g.* adiabatic coupler can only have 50% or 100% splitting ratios) and cannot be tuned once fabricated. Moreover, they often require long structure to ensure the adiabaticity of the mode transition.

In this paper, we propose and analyze a compact optical waveguide coupler structure that possesses both of the advantages mentioned above - the wavelength flattened response and the tuning capability. The fabricated device showed a flattened wavelength dependence over the wavelength 1.55-1.6 um and a wide tuning range of the power coupling to the cross port. To the best of our knowledge, this is the first time a tunable and broadband coupler has been demonstrated.

II. DESIGN OF THE TUNABLE BROADBAND COUPLER

A. *Principle of the tunable broadband coupler*

The tunable broadband coupler consists of two parts: an asymmetric MZI with the lengths carefully chosen and a thermal tuner laid vertically on top of one arm of the MZI, as illustrated schematically in Fig.1. The coupling region includes two sections with the lengths of L_1 and L_2. Moreover, the phase between the two coupling regions are introduced by the length difference between two arms (ΔL) and can be added

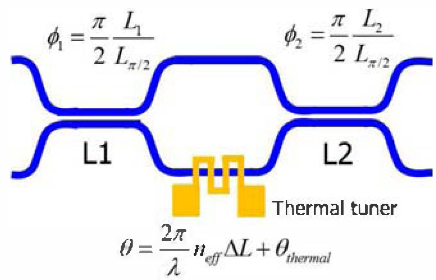

Figure 1. Schematic structure of a tunable broadband coupler

further more by the phase shift $\theta_{thermal}$ induced by the thermal tuner. As analyzed in [6], the power splitting ratio S is given by $S = \cos^2\frac{\theta}{2}\sin^2(\phi_1+\phi_2)+\sin^2\frac{\theta}{2}\sin^2(\phi_1-\phi_2)$ where we define $\phi_1 = \frac{\pi}{2}\frac{L_1}{L_{\pi/2}}$, $\phi_2 = \frac{\pi}{2}\frac{L_2}{L_{\pi/2}}$ and $\theta = \frac{2\pi}{\lambda} n_{eff}\Delta L + \theta_{thermal}$. The term $L_{\pi/2}$ indicates the coupling length corresponding to a 100% coupling into the cross port for a single directional coupler. Notice that all the terms appeared in the expression of S are dependent on the wavelength, the structure geometry and also the thermal phase shift. This mechanism, therefore, enables the possibility of engineering the wavelength response by waveguide geometry design, as well as enabling the capability of tuning the splitting ratio by thermal effect adjustment.

B. *Design of the tunable broadband coupler*

The structure of the tunable broadband coupler is shown in Fig. 2. The waveguide cross sectional dimensions are chosen to be 400 nm. The waveguides are fully etched to reduce etch depth variations. The gap between the two arms in the center region was kept at 50 um, that is sufficiently far to ensure a high temperature difference and thus allows an efficient tuning by the heater.

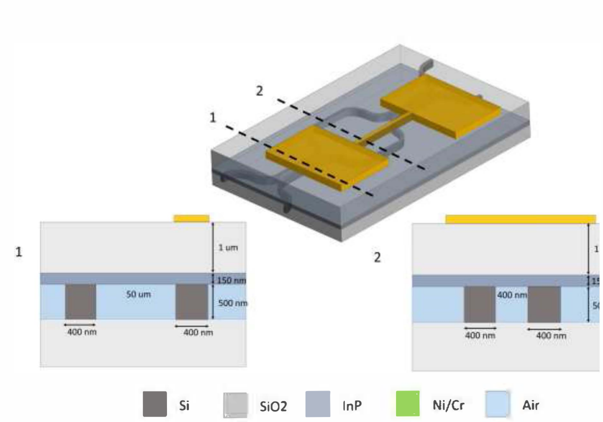

Figure 2. Schematic structure and the cross sections of the tunable broadband coupler on heterogeneous silicon platform.

A commercial software (FIMMWAVE, Photon Design, UK) employing a Finite Differences Method [7] was used to simulate the propagation of the modes through the coupler and then MATLAB is used to calculate the splitting ratio. The lengths of the coupling regions (L_1 and L_2) and the delay path difference (ΔL) are optimized to obtain the most flattened wavelength response of the splitting ratio, as shown in Fig. 3.

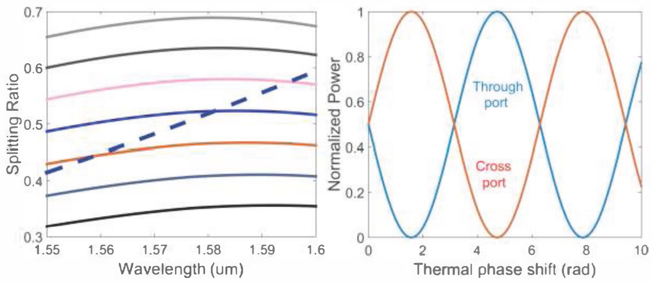

Figure 3. Simulation results on a tunable broadband coupler with L1 = L2 = 63 um and ΔL = 0.13 um. (Left) Splitting ratio versus wavelength of the tunable broadband couplers. The solid curves correspond to different thermal phase shifts. A wavelength response curve of a non-broadband coupler is also plotted (dashed-line) for comparison. (Right) Tuning the output power from through/cross ports with thermal tuning.

III. Experiment and Discussion

A. Device fabrication

The couplers were fabricated on 500 nm SOI with 1 μm buried oxide layer. Deeply etched waveguides were patterned using 248 nm DUV lithography. A III-V epitaxial layer bonded to the top silicon as per the heterogeneous silicon process [8, 9]. The III-V substrate was then removed using mechanical polish and wet-etch down to the thin n-InP layer. A buffer layer of SiO_2 was deposited by PECVD. The fabrication was completed with the last step of Ni/Cr deposition onto the top SiO_2 layer. The SEM image in Fig. 4 shows that the fabrication was highly precise.

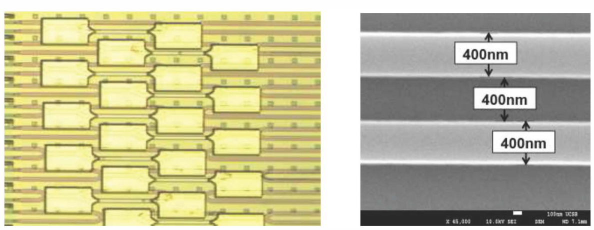

Figure 4. (Left) Top-down microscope image of a set of 10 tunable broadband couplers. (Right) SEM image before III-V bonding step shows the waveguide dimensions exactly as designed.

B. Measurement result and discussion

We characterized the performance of the fabricated devices using the measurement setup illustrated in Fig. 5's top figure. Notice that a polarization maintaining (PM) fiber was preliminarily rotated to align the fast axis to the horizontal axis in order to ensure that only TE mode was excited into the waveguide.

The measurement of the wavelength response and the thermal tuning performance are respectively shown in Fig. 5b left and right plots. The fabricated coupler showed a flattened response to the wavelength (less than 10% varying over 50 nm bandwidth) and the coupling power to cross port can be tuned over a wide range (10%-70%).

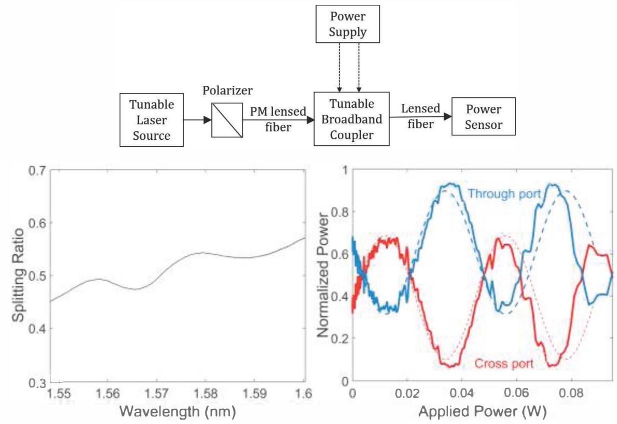

Figure 5. (Top) Measurement setup to characterize the coupler (Bottom) (Left) Measured plot of wavelength versus splitting ratio. (Right) Measured output power from through/cross ports vs. power applied to the thermal tuner with the adjusted simulation curves (dashed-lines)

However, the flatness is worse than the simulation result. This discrepancy is due to the mismatch of the coupling strength (reflected in the length $L_{\pi/2}$) between the simulation and the reality. This mismatch also resulted in the thermal tuning performance of the coupler as shown in Fig 5 bottom-right. Taking into account this mismatch, we obtained the adjusted simulation tuning (dashed) curves which fits very well with the measurement result (solid) curves.

IV. Conclusion

We analyzed and successfully demonstrated a coupler in silicon photonics that possesses a flattened response (splitting ratio variation less than 10% over 50 nm) to wavelength and has the ability to tune the power splitting ratio thermally over 10-70% range. In the future, by adjusting the design to compensate the simulation discrepancy, a flatter wavelength response and the tunability over 100% can certainly be achieved. Although the coupler was specifically demonstrated on silicon photonics, the principle and design is also applicable to any photonics platform.

Acknowledgments

The authors would like to thank Robert Lutwak, Daniel Blumenthal, Chong Zhang, Daryl Spencer, Michael Davenport and Michael Belt for many fruitful discussions and useful help. This work is supported by DARPA MTO.

References

[1] A. Yariv, P. Yeh, "Photonics: Optical Electronics in Modern Communications", Oxford, 6th Edition, 2006.

[2] J.K. Doylend et al., "Tunable ring resonators for silicon Raman laser and amplifier applications", Proc. of SPIE vol. 6896, 68960Q, 2008.

[3] P. Orlandi et al., "Tunable silicon photonics directional coupler driven by a transverse temperature gradient", Opt Lett vol. 38 (6), 2013.

[4] V. M. N. Passaro et al., "Polarization-insensitive directional couplers based on SOI wire waveguides," The Open Optics Journal 2(1), 2007.

[5] Solehmainen, K. et al., "Adiabatic and Multimode Interference Couplers on Silicon-on-Insulator", Photonics Technology Letters, vol. 18 (21), 2006.

[6] K. Jinguji et al., "Mach–Zehnder interferometer type optical waveguide coupler with wavelength-flattened coupling ratio," Electron. Lett., vol. 26, pp. 1326–1327, 1990

[7] FIMMWAVE, Photon Design Ltd, http://www.photond.com.

[8] H. Park, et al., "A Hybrid AlGaInAs Silicon Evanescent Amplifier," IEEE Photon. Technol. Lett. 19(4), 230–232, 2007.

[9] A. W. Fang, et al., "Single-Wavelength Silicon Evanescent Lasers," IEEE JSTQE 15(3), 535–544, 2007