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Nanoscale couplers for large scale photonic integrated circuitry

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Abstract— **A compact, efficient nanophotonic coupler, and its application to programmable photonic integrated circuitry is presented. The coupler operates on the partial coupling of the evanescent wave of a total internal reflection into a continuing waveguide**

I. INTRODUCTION

Important inter-related frontiers for photonic integrated circuitry include the increased level of integration, higher yield and smaller footprint building blocks. A common task is the splitting of one optical signal, in one waveguide, into two components in two waveguides, and this must be done with high efficiency and minimal back-reflection. Currently, the conventional approach to this problem is the adiabatically tapered “Y” coupler [1-3]. Using this configuration it is common to achieve very high efficiencies with virtually no back-reflection in splitters that are several hundreds of microns in length. Resonant structures may also be included in Y-type couplers to reduce the size, however not necessarily the group delay of the device [4]. Parallel waveguide based directional couplers have also been realized in a variety of material systems [5-7], and in these structures gratings may be included to provide wavelength selectivity and shorter length scales [8]. Recently, compact “air trench” tapers have been demonstrated for low index contrast systems with efficiencies in the high 90% range that occupy approximately 30x30 um areas [9]. In Reference 9, the authors appropriately point out the problem of loss in photonic crystal couplers. Careful sidewall control and tapers contribute to low Fresnel back-reflections and loss in Reference 9.

The authors have been developing an active 1.5 micron wavelength photonic true time delay device in the InGaAsP/InP material system that requires a right angle split of the mode [10] at a T intersection of two ridge wavguides as shown in Fig. 1. In this letter the authors discuss a compact coupler design based on frustrated total internal reflection to achieve an equal split. In contrast to the coupler shown in Fig. 1, the trench is etched deeply to completely overlap the waveguide mode, but its width is reduced to frustrate the total internal reflection and allow coupling to the continuing waveguide. In this configuration arbitrary splitting ratios can be achieved through careful control of the trench width. Efficiencies in excess of 95% are predicted in a 2 micron footprint.

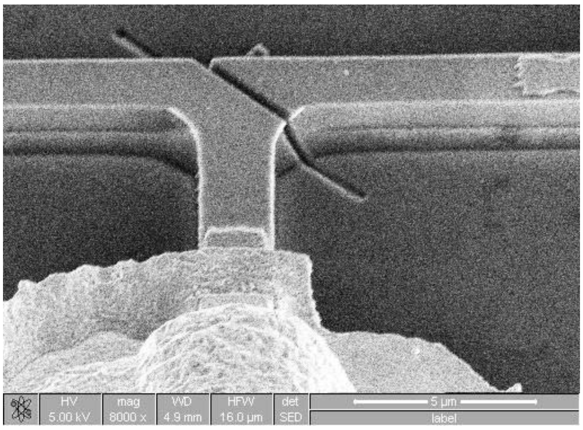

Figure 1. T intersection of ridge waveguides in AlGaAsP/InP. In the coupling scenario proposed here the wave travels from left to right across the top of the T. At the intersection a 45% trench deflects part of the signal down into the stem of the T. With the correct trench width, the total internal reflection is frustrated by a short gap and the remaining signal continues to the right.*)*

The coupler operates on the partial coupling of the evanescent wave of a total internal reflection into a continuing waveguide, so that half the signal from the evanescent field is coupled into the continuing waveguide and therefore only the remaining half is reflected into the side waveguide. For material systems with low index of refractions an air gap of reasonable dimensions (>200 nm) can be used. Importantly, for higher index III-V semiconductor waveguides with high refractive index, the gap can be filled with a dielectric using, for example, plasma enhanced vapor deposition (PECVD) [11,12] thereby increasing the required gap width for 3 dB coupling

II. DESCRIPTION

The coupler was designed using finite difference time domain software installed on a Linux based platform. The complex optical scattering problem was solved in two dimensions, and design variables included different material systems, coupler dimensions and coupler materials. Reported here, however, is one geometry, a 45 degree cut aligned to couple signal into the branch of the “T”. For most material systems used in integrated photonics, such as III-V semiconductors, lithium niobate, SiO2, silicon and polymers, the cut is totally internally reflecting. Therefore, in the FDTD runs, the width of the trench is scanned numerically to find the desired coupling percentage, which for our application is 50%. Figure 2 shows a contour plot of the waveguide "T", a 105 nm air gap, and the resulting electric fields in an InGaAsP/InP multiple quantum well epitaxial waveguide structure. In these TM calculations, the ridge waveguide width was 2.5 microns. The diagonal polygon is the air trench, and the other thin polygons are power monitors for the launch, transmission and reflection of the incident wave.Improved manufacturability and less sensitivity to wavelength and gap tolerances is attained by depositing a dielectric to fill the etched gap. For example, in the InGaAsP/InP case above, the use of Al2O3 (n=1.75) extends the gap dimension to 137 nm.

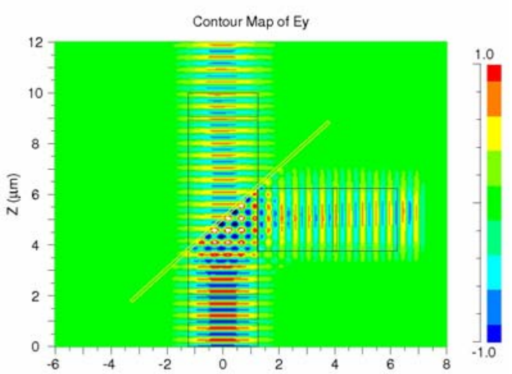

Figure. 2. Finite Difference Time Domain calculations for a 3 dB coupler in an AlGaAsP/InP ridge waveguide using an air gap of 105 nm.

The role of frustrated internal reflection in the operation of the coupler discussed herein can be described through an analytic derivation based on a plane wave approximation to the mode. For our configuration the barrier index and incident angle (45-degrees) should be chosen to result in total internal reflection had the thickness of the barrier been large. Figure 3 is a family of curves of the resulting 3dB coupling solution. It plots the necessary trench width as a function of the waveguide index of refraction for a variety of fill materials: air (n=1), PMMA (1.48), SU8 (n=1.57), sapphire (n=1.75), and zirconium (n=2.1). The ranges of the plotted lines are limited by the domain over which this analysis holds, i.e., total internally reflecting waveguide – trench interfaces. Note that in the range of polymer and glass waveguide indices, near 1.5, air trenches provide trench dimensions that can be readily fabricated. With waveguide indices typical of semiconductor waveguides (n>3), the air trench approach results in great challenges for high aspect ratio etching. The fabrication difficulty can be reduced if the gap is filled with a higher index material.

III. CONCLUSION

A novel 1x2 photonic coupler has been presented. The coupler operates on the partial coupling of the evanescent wave from a total internal reflection interface into a continuing waveguide, and was analyzed both by finite difference time domain calculations and by the closed form expression for frustrated total internal reflection. These analyses are in good agreement.

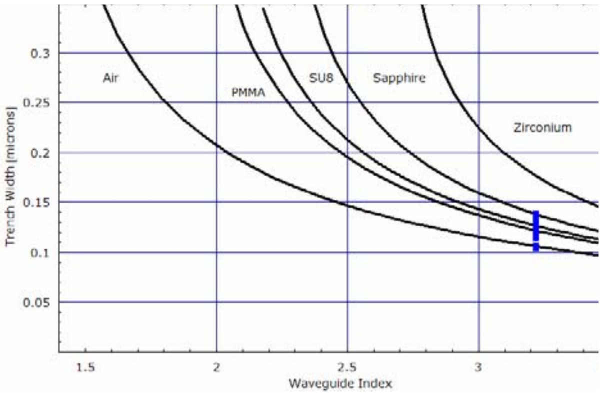

Figure. 3. The gap dimension required for 3 db coupling as functions of the waveguide index for different gap materials as predicted by Equation 1. The blue squares represent validation of the model through 2D FDTD analysis.

REFERENCES

[1] W. K. Burns, R. P. Moeller, C. H. Bulmer and H., Yajima, "Optical waveguide channels in Ti-diffused LiNbO3," Appl. Opt. 19, 2890-2896 (1980).

[2] M. Kuznetsov, "Radiation loss in dielectric waveguide Y-branch structures," J. Lightwave Technol. LT-3, 674-677 (1985).

[3] M. Maeda, T. Hirata, M. Surfiuro, M. Hihara, A. Yamaguchi, H. Hosomatsu, "Photonic integrated circuit combining two GaAs distributed Bragg reflector laser diodes for generation of the beat signal," Jpd. J. Appl. Phys. Part 1: Regular Papers and Short Notes and Review Papers 31, 183-185 (1992).

[4] T. D. Ni, D. Sturzebecher, A. Paolella and B. Perlman, "Novel polymer optical couplers based on symmetry mode mixing," IEEE Photon. Technol. Lett. 7, 1186-1188 (1995).

[5] A. Hardy and W. Streifer, "Coupled mode theory of parallel waveguides," J. Lightwave Technol. LT-3, 1135-1146 (1985).

[6] J. P. Donnelly, H. Haus and L. Molter, "Cross power and crosstalk in waveguide couplers," J. Lightwave Technol. LT-6, 257-268 (1988).

[7] M. Raburn, B. Liu, K. Rauscher, T. Okuno, N. Dagli and J. E. Bowers, "3-D photonic circuit technology," IEEE J. Sel Areas Quantum Electron. 8, 935-942 (2002).

[8] S. W. Ahn and S. Y. Shin, "Grating assisted codirectional coupler filter using electrooptic and passive polymer waveguides," IEEE J. Sel Areas Quantum Electron. 7, 819-825 (2001).

[9] S. Akiyama, M. A. Popovic, P. T. Rakich, K. Wada, J. Michel, H. A. Haus, E. P. Ippen and L. C. Kimerling, "Air trench bends and splitters for dense optical integration in low index contrast," J. Lightwave Technol. 23, 2271-2277 (2005).

[10] Jian Tong, Kent Wade, Duncan MacFarlane, Scott McWilliams, Gary A. Evans and Marc P. Christensen, "Active Integrated Photonic True Time Delay Device," IEEE Photonics Technol. Lett. 18, 1720-1723 (2006).

[11] L. Koltunski and R. A. B. Devine, "Infrared properties of room-temperature-deposited ZrO2," Appl. Phys. Lett. 79, 320-322 (2001).

[12] S. X. Lao, R. M. Martin, and J. P. Chang "Plasma enhanced atomic layer deposition of Hfo2 and ZrO2 high-k thin films," J. Vac. Sci. Technol. A 23, 488-496 (2005).