ULTRA-COMPACT OPTICAL WAVEGUIDE COUPLERS FOR MONOLITHIC INTEGRATION

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Monolithic integration of waveguides for on-chip optical signal processing is a technology fundamental to enhanced optoelectronic circuit functionality. A major drawback to monolithic optics, however, has been the large size (typically many millimeters) required for optical directional couplers with their associated input/output branching guides,[1] which is incompatible with the relatively high cost of III-V semiconductor materials. This year two quite different, yet complementary, new techniques were demonstrated for making extremely compact couplers suitable for monolithic integration.

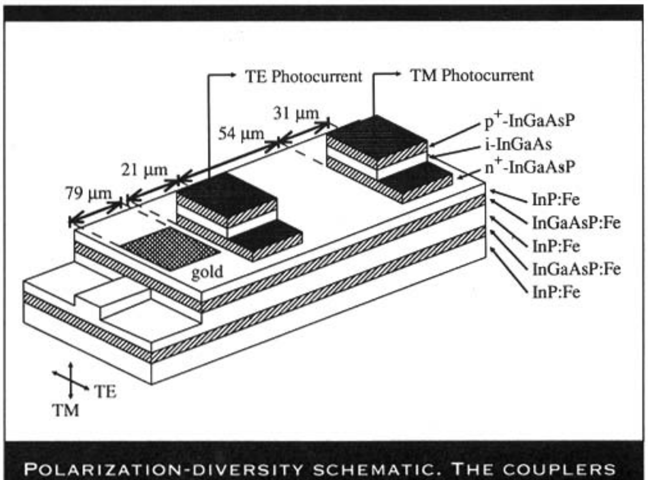
One technique employs a vertical coupler[2] formed by two waveguides grown above one another with a thin spacer layer between them. The thin spacer results in strong coupling between the guides, substantially reducing the device length. Such strong coupling requires the precise control of spacer thickness achievable with epitaxial growth processes, which is not available with the lithographic techniques used for conventional lateral couplers. To eliminate difficulties in separating the two coupler optical outputs, integrated photodetectors are used for optical-to-electronic conversion of one coupler output.

Vertical couplers were used to realize a polarization diversity detector, which produces two photocurrents proportional to the input intensities in each of two orthogonal polarization states. The functionality is necessary for polarization-independent coherent receivers.[3] The device, shown in the figure, consists of an input rib optical waveguide, a vertically-defined coupler followed by a vertically-coupled *pin* photodiode, and a second coupler/detector pair.[2] A gold cover on the first coupler spoils TM coupling, ensuring that only TE-polarized light couples into the first detector; the second coupler/detector collects the remaining TM light. Device lengths are only 79 + 21 and 54 + 31 μm for the two coupler + diode pairs, which are at least 10 times smaller than conventional coupler and comparable to electronic components (FET gate widths). Device fabrication is simple, involving a single epitaxial growth followed by *conventional processing with no critical coupler gap definition*. Fabricated detectors work extremely well, with on-chip quantum efficiencies >75% and polarization crosstalk as low as −11.9 dB(TE) and −17.6dB(TM). Simulations predict that even lower crosstalk (−15dB TE, −27dB TM) can be realized.

For situations in which vertical couplers cannot be used, short lateral couplers can be made by eliminating the gap between coupled guides, so that the coupler consists of a single, bimodal channel guide. However, it has not been possible to achieve low-loss junctions between such "zero-gap" couplers and the deeply-etched waveguides required for compact input/output branching (*i.e.*, small bend radii). Groups at Bellcore and Delft have now shown that by using coupler guides wide enough to support many modes, and making use of the self-imaging in such guides,[4] ultra-compact couplers with low-loss, fabrication-tolerant junctions can be achieved.

At Bellcore,[5] we fabricated 8 μm wide GaInAsP couplers supporting four modes at λ = 1.52 μm. Using 300 μm radius bends with optimized junction offsets, the total 3 dB coupler length is 484 μm (including branching guides), significantly shorter than conventional couplers. Low on-chip insertion losses (0.3 dB) and coupler crosstalk (−30 dB) were measured. Moreover, device performance was shown to be insensitive to polarization, wavelength, or temperature, which is important for many applications. The Delft group[6] fabricated Al_2O_3/SiO_2 couplers with 12-14 μm coupler width supporting 7-9 modes. These devices exhibited low insertion losses (0.2dB) and crosstalk (−18 dB) as well.

Two approaches leading to ultra-compact directional couplers suitable for monolithic integration have been demonstrated. We envision a wide range of applications for these devices. For example, integration of the multimode 3 dB splitters with polarization-diversity detectors based on vertical couplers will result in extremely small



POLARIZATION-DIVERSITY SCHEMATIC. THE COUPLERS CONSIST OF InGaAsP WAVEGUIDE LAYERS (CROSS-HATCHED) SEPARATED BY AN InP SPACER (CLEAR).

optoelectronic circuits for balanced, polarization-insensitive coherent detection.

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Ultra-Low-Power Integrated Acousto-Optic Filter

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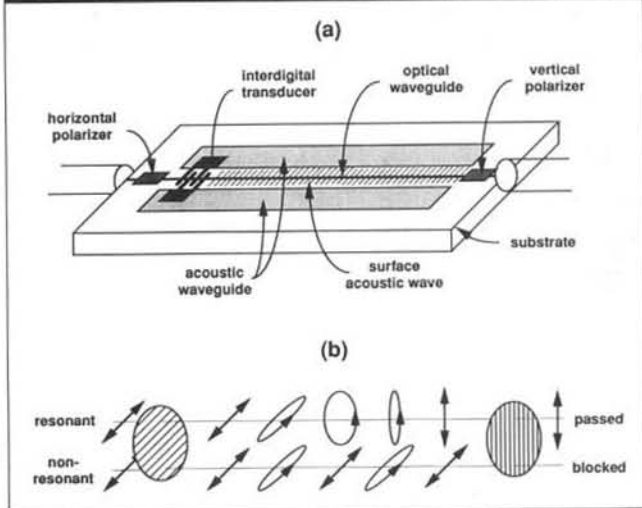
The acousto-optic filter has gained increasing attention in wavelength-division multiplexed optical communication because it offers the unique and powerful capacity to extract many different wavelength channels (simultaneously and independently) from one optical fiber and divert all or part of each signal to a second fiber. This parallel-processing capability means that each wavelength in a fixed fiber network has an independently configurable matrix of interconnections.[1]

The problem with commercially available bulk-crystal components, in which a large volume acoustic wave interacts with a wide optical beam, is their notoriously high power consumption. By employing the miniaturization techniques of integrated optics and integrated acoustics, we[2] and others[3] have systematically decreased the size and dimensionality of *both* the optical and acoustic beams, until both beams have become more or less one-dimensional waveguided modes. The net effect of all this size reduction (except, it should be stressed, in the irreducible dimension of interaction length) is a dramatic reduction in the power requirement for optical filtering.

To date, we have demonstrated nearly complete polarization conversion (resulting in wavelength selection without excess loss) with only 8 mW of applied RF power.[2] This is about 250 times less power than commercial bulk-optic filters require, and 25 times less power than integrated optic filters, which do not have acoustic waveguides. The acoustic transducers can support about 1 watt of power, allowing for up to 100 channels to be switched at a time.



(a) Schematic of the acousto-optic filter employing guided surface acoustic waves to flip the polarization state of a narrow band of guided optical wavelengths, and (b) polarization evolution along the device for resonant and non-resonant wavelengths.

The integrated acousto-optic filter is shown schematically in the accompanying figure. An incoming optical beam is fiber-coupled into a several-micron-wide titanium-indiffused optical channel on a lithium niobate substrate, prepared in a specific polarization state (shown horizontal here). A miniature radio-frequency transducer imbedded in a 100 µm-wide acousto waveguide, the walls of which are also formed by deep titanium indiffusion, generates a confined surface acoustic wave. For those wavelengths that experience phase-matched photoelastic polarization conversion (*i.e.*, for that narrow band of wavelengths for which the interaction provides constructive accumulation of polarization change along the device), the incoming polarization is flipped [to vertical in Part (b) of the figure] and passes through an orthogonal beam-blocking polarizer before exiting the filter. Unselected (nonresonant) wavelengths are blocked. Polarization-independent versions of this filter, employing polarizing beamsplitters instead of pass-or-fail polarizers, also have been made in low-power configurations during the last year.[3]

With continued improvements in switching power and other measures of performance, including wavelength crosstalk and ease of manufacture, the acousto-optic filter may well have a central role in future broadband, wavelength-multiplexed optical networks.

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