Multi-mode interference optical devices based on self-imaging effects

of the micropipette, which can have orifices at the tip of <10 nm. The largest intensity detected thus far from our devices was 4.2 footlamberts without any engineering optimization such as taking care to encapsulate the material so that interaction with oxygen and humidity is minimized. Future improvements in both the size and the intensity of the light source are expected, especially in view if the fact that, in the past two years, there have been significant advances in polymer electroluminescent materials[4] that can be formed in the tip of even the smallest (<10 nm) pipettes.

If the light source we presently have was used together with near-field optics for optical memory applications, nearly a gigabyte of information—or the entire *Encyclopedia Britannica*—could be stored on a dimension of 1 cm^2.

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COMMUNICATIONS & SWITCHING

Multi-Mode Interference Optical Devices Based on Self-Imaging Effects

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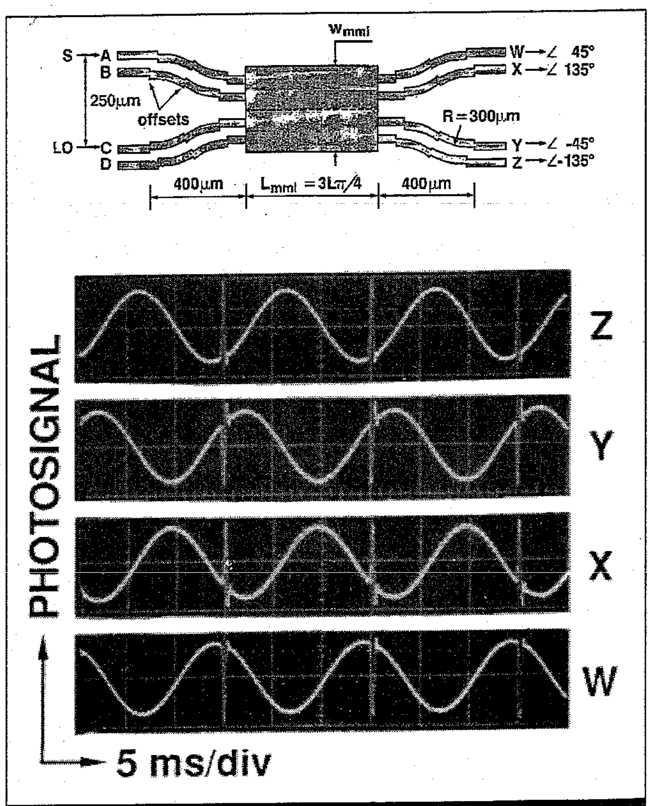
As opto-electronic integrated circuits (OEICs) become a reality, there is an increasing need for optical signal routing and signal processing devices with smaller dimensions, improved fabrication tolerances, and polarization-independent operation. Recently, several papers reported on multi-mode interference (MMI) 2×2 directional couplers that, in contrast with conventional two-mode interference (TMI) couplers, can fulfill all of the above requirements. Insertion losses as low as 0.5 dB and extinction ratios better than 30 dB have been obtained[2,3] with very compact, polarization-independent fabrication tolerant devices. The key feature of the high performance of these couplers is the self-imaging effect by multi-mode interference. Self-imaging[1] is a property of multimoded waveguides by which the exciting field at the entrance will be reproduced (either replicated or mirrored, single or n-folded) at periodic intervals along the propagation direction of the guide.

This year, the incorporation of these MMI couplers into higher level OEICs has been reported by several laboratories. Two cascaded 3-dB MMI couplers were used to realize a high-performance polarization-independent Mach-Zehnder quantum well electro-optic switch.[4] An ultra-compact monolithically integrated polarization-diversity receiver was reported[8] that featured one single polarization-independent 3-dB MMI coupler.

In addition to this, novel MMI waveguide structures have been developed. Beam splitters and recombiners based on multi-mode propagation phenomena have been demonstrated[5] in hollow waveguides at 10.6 μm wavelength. An ultra-short 1×2 optical power splitter based on MMI was reported[6] that featured low losses (≤ 1dB), low unbalances (≤ 0.15dB) and polarization insensitivity for remarkably



The schematic layout of the 4×4 90° optical shows one single MMI section of width W_{MMI}=21.6 μm and length L_{MMI}=930 μm, resulting in a very compact device. Bottom: When inputs A and C are excited by light from a signal and local oscillator source, the IF beat signals in the four outputs satisfy the phase quadrature condition as evidenced by the oscilloscope traces.

short (20 μm for Si-based, 60 μm for InP-based) devices.[6] Also, an all-passive 90° 4×4 optical hybrid has been realized using self-imaging in InP-based waveguides.[7] The hybrid revealed an insertion loss better than 1 dB and is very compact, consisting of one single multi-moded interference section (see top figure). An excellent splitting ratio of 0.26/0.25/0.25/0.24 and a phase deviation of ±3° from the ideal condition were obtained in direct relation to the fact that the quadrature condition is inherent to the four-fold self-imaging (see bottom figure). Such a hybrid may constitute the basis of a phase-diversity optical receiver.

Following initial reports on MMI directional couplers, this year has shown their compatibility with other devices and how their incorporation can boost the functionality of higher level OEICs. Besides, the continuing investigation of MMI phenomena has led to several novel devices based on self-imaging. We thus envisage an increasing range of low-loss, small-size, process-tolerant optical devices based on the versatile MMI phenomena.

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Sidelobe-Suppressed Acousto-Optic Filter

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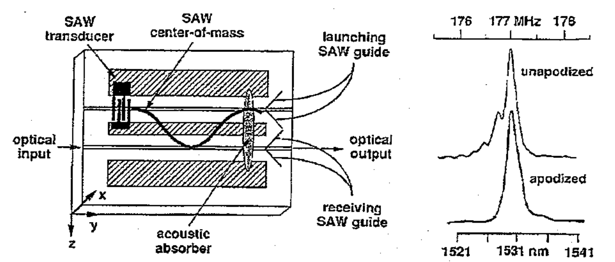
The integrated acousto-optic filter (AOF) has found many applications in optical signal processing, from fast scanning optical spectroscopy to routing in wavelength-division-multiplexed (WDM) systems, to femtosecond pulse shaping.[1,2] Devices fabricated by integrated optical and acoustic technology on x-cut $LiNbO_3$ have the ability to filter, or to switch between output ports, one or many independent nanometer-wide wavelength channels. Wavelength-selective switching in the AOF is achieved by a resonant photoelastic effect that results in a polarization flip for a narrow band of phase-



SAW coupler apodized integrated AO filter. Upper trace shows typical AO filter response at 1531 nm without apodization, lower trace with apodization.

matched wavelengths for which the applied RF acoustic frequency provides the exact momentum transfer required to affect a polarization flip in the birefringent host medium. The integrated AOF requires only about 10 mW per channel, even in the highly integrated polarization diversity configuration that provides polarization insensitive wavelength-selective switching. Such low power demand means that parallel processing of many wavelength channels at a time is possible without undue heating. Recent results, described below, have eliminated the major drawback of AO filters: residual out-of-band transmission.

The most intractable problem to date has been that the characteristic transmission spectrum of the AOF exhibits a sinc-squared profile, with many secondary peaks flanking the main lobe, falling off in a slowly decaying envelope, and leading to interchannel crosstalk among densely packed optical communication bands. Recent results from Bellcore's group on integrated acousto-optics,[3] echoed shortly thereafter by researchers at the University of Paderborn in Germany,[4] have shown that it is possible to sharply reduce sidelobe levels by apodization of the acousto-optic interaction strength. Tapering the acoustic power profile, so that the abrupt onset and cutoff of the AO interaction in standard filter designs is replaced by a gradual rise and fall of the coupling strength, removes the high frequency structure of the transmission spectrum, resulting in deep sidelobe suppression. A tapered acoustic intensity profile was obtained by generating the acoustic beam—not in an acoustic waveguide centered over the optical waveguide, as in usual AOF designs, but in a nearby parallel acoustic waveguide that is weakly coupled to the customary acoustic waveguide. The resulting composite acoustic structure, known as an acoustic directional coupler, causes acoustic energy to smoothly oscillate between the two acoustic waveguides so that, from the point of view of the "receiving" acoustic waveguide, the acoustic power density starts at zero, increases sinusoidally to a maximum, and then falls again to zero in the reverse process. The "center of mass" of the acoustic beam follows the path shown in the figure.

Theoretical modeling suggested that a "raised cosine" taper would result in a 10 dB reduction in sidelobe levels from 10% of peak intensity to only 1%. A 10-fold reduction was indeed observed, though from a high of 30% sidelobes in an unapodized 19-mm-long filter to only 3%, as shown in the accompanying figure.

Nothing is free: The filter bandwidth increases by 57%