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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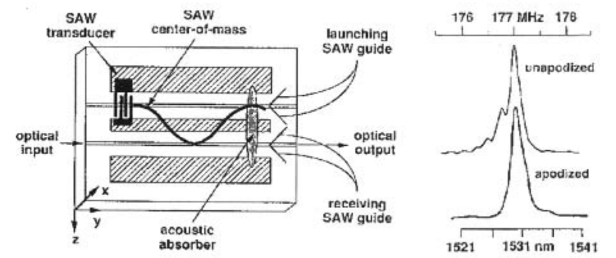
The integrated acousto-optic filter (AOF) has found many applications in optical signal processing, from fast scanning optical spectroscopy to routing in wavelength-division-multiplexed (WDM) systems, to femtosecond pulse shaping.[1,2] Devices fabricated by integrated optical and acoustic technology 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-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.



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

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%

(by a factor of $\pi/2$) and the power requirement more than doubles (by a factor of $\pi^2/4$), because the effective interaction length of the device is shortened due to the softened edges of the interaction region. This is a small price to pay for a tremendous improvement in channel isolation.

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Monolithically Integrated 21-Wavelength DFB Laser Array with a Star Coupler and Optical Amplifiers

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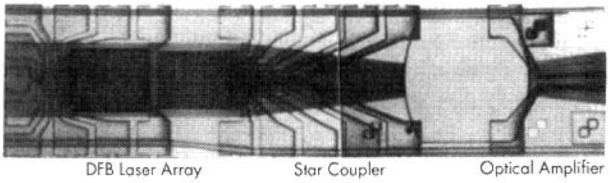
We have reported previously multi-wavelength distributive feedback DFB laser arrays with as many as 20 wavelengths on a single chip fabricated by the use of strained-layer InGaAs/InGaAsP multi-quantum wells.[1] A wavelength span as large as 131 nm in the 1.5 μm wavelength region, a 3 dB modulation bandwidth as high as 16 GHz, and a linewidth as small as 180 kHz have been obtained. More recently, we have demonstrated monolithic integration of the laser array with a star coupler and optical amplifiers on the same chip to simplify fiber pigtailing. These devices have potential application for high density wavelength divisive multiplexing WDM systems, as well as for optical networks using wavelength routing.

Traditionally, the increased transmission bandwidth has been accomplished by time-division-multiplexing through the increase in the transmission speed. This is because the cost in transmission per bit per km of fiber has been decreasing continuously up to a speed of 2.5 Gbit/sec. As a result, the transmission capacity has been increasing at a rate about doubling every year from 1980 through 1988. Recently, commercial systems at rates of 1.2 and 1.7 Gbit/sec have been installed, and 2.5 Gbit/sec systems are planned for new installations. Although systems with even higher rates at 10 Gbit/sec have been demonstrated in the laboratories, commercial systems probably will not be available in the near future due to the unavailability of high speed electronics.



A micrograph of the top view of the monolithically integrated 21-wavelength DFB laser array with a star coupler and optical amplifiers.

Because of the broad optical bandwidth (30 THz) available in the low-loss transmission window of the optical fiber, it is desirable to exploit the fiber bandwidth by wavelength division multiplexing (WDM) to overcome the electronic limitations, thus to further increase the transmission capacity. For example, early WDM transmission experiments at 10, 16, and 100 wavelength channels with the aggregated capacity of 20, 32, and 62 Gbit/sec,[2-4] respectively, were reported in 1985, 1988, and 1990. In the last two years, there were two major breakthroughs that make the WDM even more attractive. They are (1) the Er-doped fiber amplifiers (EDFAs), and (2) strained layer multiple quantum well laser diodes (SL-MQW-LDs). The EDFA eliminates the need of electronic regenerators, whereas the SL-MQW-LDs have very low threshold currents and large gain spectral width that permit multiple wavelength laser arrays to be fabricated on a single wafer. Furthermore, the EDFA has sufficient bandwidth to amplify many wavelength channels simultaneously; thus, it is cost effective in conjunction with WDM systems.

Distributed feedback laser arrays are attractive as multiwavelength light sources for wavelength division multiplexed systems because a single TE cooler can be used to keep the relative wavelength spacing constant that facilitates a simple wavelength control and stabilization. By taking advantage of the wide gain width of the strained layer multiple quantum wells, we have recently fabricated multiwavelength DFB laser arrays with as many as 20 wavelength channels in one array.[1] The channel spacing ranged from 3-7 nm, which can allow four to eight channels within the band of the Er-doped fiber amplifiers.

To make the DFB laser diode array a practical device, it is desirable to combine the multiwavelength output into a single-mode fiber pigtail. Recently, we have investigated monolithic integration of a multi-wavelength DFB laser diode array with a star coupler and an optical amplifier on one chip. After amplification, the combined signals in all wavelengths in the output waveguides of the star coupler can then be coupled into a single-mode fiber pigtail. The top view of a finished integrated laser array chip is shown in the figure. The 21-wavelength DFB laser array is connected to the star coupler through passive waveguides. Quantum well optical amplifiers were inbeded in two output waveguides near the center of the star coupler, and the remaining output waveguides are passive. The star coupler is formed by radially spacing the input and output waveguides with an angular increment of 0.6° on a 750 μm radius circle centered at the middle of the input and output waveguides. The active layer of the DFB lasers and the optical amplifiers consists of six compressive-strained $In_{0.7}Ga_{0.3}As$ wells. The gratings of different periods are generated by e-beam lithography.

Preliminary results show that the cw lasing wavelengths spans from 1512-1578 nm for 18 channels with threshold currents varying from 14-55 mA. The remaining three lasers have much higher thresholds. The channel spacing is 3.7 nm with a standard deviation of 0.38 nm. The side mode suppression ratio is typically better than 35 dB.