measured with the experiment carried out at 12 GHz.

In comparison to their AO counterparts, the unique advantages associated with the MO Bragg cells are: 1) A much larger range of tunable carrier frequencies may be obtained by varying the DC magnetic field. Such high and tunable carrier frequencies with the MO devices allow direct processing at the carrier frequency of wideband RF signals and eliminate the need for indirect processing via frequency down-conversion as is required with the AO devices. 2) A large MO bandwidth may be realized by means of a simplier transducer. 3) Much higher and electronically tunable modulation/switching and scanning speeds are achievable because the velocity of propagation for MSWs can be higher than that of SAWs by one- to two-orders of magnitude. The guided-wave MO Bragg cells are also being integrated in a YIG-GGG waveguide substrate $0.2 \times 1.5 \times 2.0$ cm^3 in size with an ion-milled waveguide lens pair[6] to form integrated MO modules similar to those based on guided-wave acousto-optics.[7]

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REFERENCES

1. See, for example, P.K. Tien, et al., Appl. Phys. Lett., 21, 394, 1972.
2. C.S. Tsai, IEEE Trans on Circuits and Systems, CAS-26, 1072, 1979.
3. D. Young and C.S. Tsai, Appl. Phys. Lett., 53, 1696, 1988.
4. C.S. Tsai and D. Young, X-band magneto-optic Bragg cells using Bismuth-doped Yttrium Iron Garnet waveguides (to be published in Appl. Phys. Lett., 54, Nov. 1989).
5. C.S. Tsai and D. Young, Appl. Phys. Lett., 54, 196, 1989.
6. T.Q. Vu, J. Norris, and C.S. Tsai, Appl. Phys. Lett., 54, 1098, 1989.
7. C.S. Tsai, J. Modern Opt., 35, 965, 1988.

Advances in waveguide photodetectors

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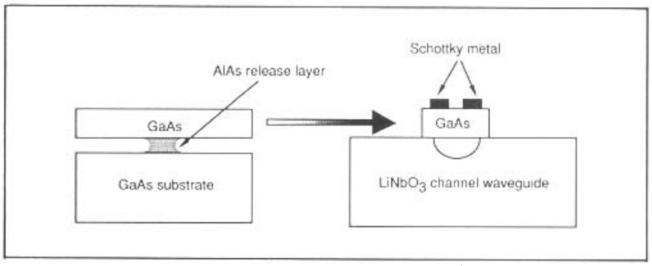
Many signal processing functions needed for future broadband optical communcations and switching networks will be most effectively realized in waveguide-based systems where optoelectronic integrated circuits serve as intelligent control points capable of recognizing and processing the optical signal as required. Fast photodetectors that can detect light in a waveguide are key to the success of these systems. The year saw significant developments in the integration of photodetectors with both semiconductor and non-semiconductor waveguides.

Advances were made in both monolithically integrated p-i-n and metal-semiconductor-metal (MSM) waveguide detectors. High speed InGaAs p-i-n waveguide taps, operating up to about 7 GHz with a −1 V bias, were integrated with InP waveguides.[1] These detectors were designed to absorb only a fraction of the guided light power, allowing most of the signal to pass into the output waveguide, and are thus suited for signal monitoring. The device geometry included a p-n junction across the waveguide that would allow the simple integration of switches to route the optical signal.

Following the introduction of high performance long wavelength MSM photodetectors using Schottky barrier height enhancement layers,[2] fast, monolithically integrated InGaAs MSM waveguide detectors were fabricated.[3] The detectors were formed on double heterostructure waveguides and we have implemented both taps using short detectors and terminal devices using longer ones. Unlike most p-i-n devices, the frequency response of the MSM is transit time limited and is thus almost independent of detector length, with both the tap and terminal configurations demonstrating an impulse response of 49 psec (FWHM) at 10 V bias.

Although semiconductors are the only choice for high speed photodetectors, properties of other materials, such as LiNbO$_3$, are more favorable for waveguides and electro-optic devices. High performance optoelectronics will combine the most favorable properties of various material systems and would therefore involve the integration and interaction of devices formed from different materials. One method of achieving this—the epitaxial lift-off technique[4]— was recently introduced: an epitaxially grown semiconductor structure is removed from the original substrate and is re-attached to another substrate through van der Waals forces.



Schematic of the lifted-off GaAs MSM photodetector on LiNbO$_3$. A GaAs epitaxial layer is grown on a GaAs substrate with an intervening sacrificial AlAs release layer. The epitaxial layer is separated from its original substrate by selective etch of the release layer (left) and is transferred to a LiNbO$_3$ substrate containing channel waveguides (right). Using standard processing steps, MSM photodetectors are then fabricated over the waveguides from the transferred GaAs layer.

It was shown that the lift-off technique does not degrade the bandwidth and the quantum efficiency of InGaAs/InP p-i-n photodiodes.[5] The lifted-off devices, with a 2 μm absorption layer thickness and a (24 × 24) μm^2 mesa area, showed a bandwidth of 13.5 GHz and an internal quantum efficiency of 90% at 1.3 μm wavelength. These results are similar to those obtained on devices of the same dimensions that were not lifted-off.

The transfer of semiconductor devices without degradation in their performance leads to the exciting possibility of integrating high performance photodetectors with optical waveguides in materials other than semiconductors. We fabricated GaAs MSM photodetectors on both glass and $LiNbO_3$ waveguides (see figure), and detected a photocurrent in response to light in the waveguide, demonstrating the optical coupling between the two.[6–7] The coupling, which was not optimized by waveguide and detector design, gave rise to an absorption coefficient of 40 cm^{-1} for a guided mode in a proton-exchanged $LiNbO_3$ waveguide; similar results were obtained on ion-exchanged glass waveguides. The ability to obtain good optical coupling between a transferred semiconductor device and an underlying waveguide lays the foundation for a new generation of integrated devices. Potential applications of this new technique have only begun to be explored.

REFERENCES

1. W.K. Chan, J.H. Abeles, K.C. Nguyen, R. Bhat, and M.A. Koza, IEEE Photonics Technol. Letts., 1, 65, 1989.
2. H. Schumacher, H.P. LeBlanc, J. Soole, and R. Bhat, IEEE Electron Dev. Lett., 9, 607, 1988.
3. J.B.D. Soole, H.Schumacher, R. Esagui, H.P. LeBlanc, R. Bhat, and M.A. Koza, to be published, Appl. Phys. Letts.
4. E. Yablonovitch, T.J. Gmitter, J.P. Harbison, and R.Bhat, Appl. Phys. Letts. 51, 2222, 1987.
5. H. Schumacher, T.J. Gmitter, H.P. LeBlanc, R. Bhat, E. Yablonovitch, and M.A. Koza, Device Research Conference, Boston, June 1989.
6. W.K. Chan, A.Yi-Yan, T.J. Gmitter, L.T. Florez, J.L. Jackel, E. Yablonovitch, R. Bhat, and J.P. Harbison, Device Research Conference, Boston, June 1989.
7. A. Yi-Yan, W.K. Chan, T.J. Gmitter, L.T. Florez, J.L. Jackel, E. Yablonovitch, R. Bhat, and J.P. Harbison, IEEE Photonic Technol. Lett. 1, 379, 1989.

Acousto-optic photonic switch

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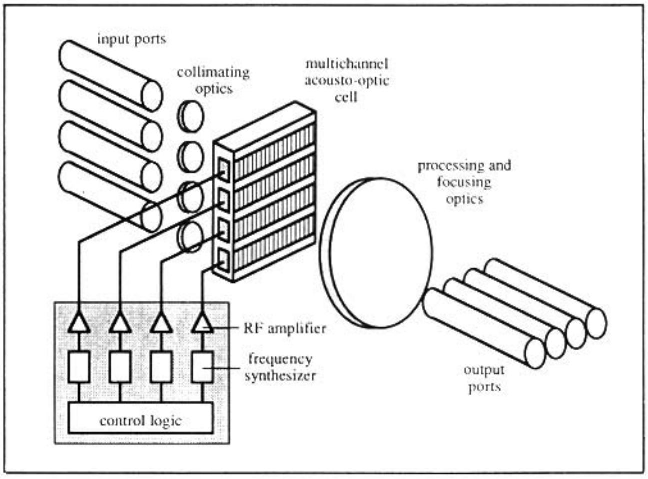
In recent years, there has been interest in developing photonic switches.[1–2] A promising class of space-division architectures is based on dynamic beam steering, where input light is deflected to one of several output ports. Such an architecture uses the three-dimensional processing capability of optics, allowing nonblocking N×N switches to be constructed with only N deflectors. In addition to the low hardware complexity, low losses are possible even for large switches because light must encounter only one deflector, regardless of the number of output ports. Optical crosstalk is due to diffractive spreading of output beams in this type of switch and, typically, only nearest neighbor contributions are significant; therefore, crosstalk can also be limited to low levels when N is large.



A 4 × 4 acoustic-optic photonic switch.

We have proposed and demonstrated the performance of a deflecting photonic switch based on acousto-optic technology.[3] The switch has good loss and crosstalk characteristics and is capable of rapid reconfiguration. In this architecture (see figure), light from a vertical array of input fibers is collimated, with each of the collimated beams interacting with a single channel in a multichannel acousto-optic (AO) cell. An acoustic wave, created by the application of an RF signal to the AO channel, induces a horizontal linear shift in the spatial phase of the light beam. This phase shifted beam then passes through a Fourier transform lens, which creates a horizontally offset image of the input fiber in the output plane. The amount of horizontal offset in the image of the input fiber is equal to the slope of the linear phase shift, which, in turn, is proportional to the frequency of the applied RF signal. Since the output ports are arranged in a horizontal line, any output port can be accessed through proper selection of the RF frequency.

In this new approach, a dedicated digital frequency synthesizer is used to drive each of the AO channels. Since the switch is nonblocking and only one hardware element is required per input port, the device implements a normal crossbar with an unprecedented hardware complexity of