Component technology for 40 GHz fibre optic systems

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Abstract
We describe the design, manufacture and performance of integrated optical modulators and InGaAs photodetectors for microwave optical systems operating up to 40 GHz. Critical design issues are examined and the achievements of current research are discussed.

Introduction
The advantages of fibre optic transmission in terms of mass, electromagnetic compatibility and, in particular, low incremental loss with distance, are well known and the exploitation of optical techniques in microwave systems is increasing rapidly. These advantages become even more compelling at millimeter wave frequencies, where the propagation loss of conventional transmission lines becomes increasingly severe. Optical transmission can open up new application areas, for example in the remote operation of antennas and in signal processing with very long (μs) time delays. The component technology required to build efficient fibre optic systems for the millimeter wave region is now becoming available and will undoubtedly lead to significant innovations in system design. In this paper, we discuss the design and realisation of integrated optical modulators and photodiodes operating at frequencies up to 40 GHz.

Microwave optical modulators
The direct modulation of semiconductor laser diodes becomes increasingly problematic at frequencies above ~15 GHz and is unlikely ever to be the technique of choice at 40 GHz. Optical transmitters for this frequency range therefore employ external laser modulation using an integrated optical device. In general a travelling-wave configuration is employed in order to achieve chirp-free modulation with the lowest possible drive power requirement.

Optical modulators for microwave frequencies have been realised both in lithium niobate and in III-V semiconductor materials. At the highest frequencies and bandwidths, however, the semiconductor devices show major advantages. This is because it is possible to fabricate structures in GaAs (and also in InP) which exhibit identical propagation velocities for the microwave and optical signals: the modulating voltage wave and the modulated optical modulation envelope therefore remain in phase over any required interaction length. In our own research, we make use of a novel configuration in which optical modulator elements provide a distributed capacitative loading on a coplanar transmission line (figures 1 and 2). This design can be optimised to provide very high modulation efficiency and a nearly perfect velocity match. To date, -3 dB (electrical) bandwidths up to 36.5 GHz have been achieved[1].

In order to provide a basis for comparison between modulators of different types and operating wavelengths, we have defined a figure of merit which compares the desired output quantity, modulation bandwidth, to the input requirement, generator voltage[1], normalised to a standard wavelength of 1 μm:

$$F = \frac{2R}{50+R}\,\frac{\Delta f}{V_\pi}\,\lambda$$

where first term defines the fraction of the applied voltage reaching the device as a result of impedance mismatch, Δf is the -3 dB electrical bandwidth, V_π is the half-wave modulation voltage and λ is the wavelength of operation. F has units GHz μm/V. Recent results for modulators exceeding 20 GHz electrical bandwidth are compared in the following table:

Author	Technology	λ (μm)	V_π	Δf_{el} (GHz)	F
Walker[1,2]	GaAs loaded line TW	1.15	4.85	25	5.9
Walker[1]	GaAs loaded line TW	1.3	6	36.5	7.9
Kotaka[3]	InP Electro-absorption	1.55	7*	40	8.8
Nees[4]	GaAs travelling wave	1.06	288	110	0.4

* 20 dB extinction ratio

Table 1. Comparison of modulators with bandwidth exceeding 20 GHz.

The results obtained using the loaded line approach show considerable potential for even wider bandwidth systems. The demonstrated modulation voltage of 5-6V peak-peak (100% extinction) is compatible with currently available solid state microwave sources. The electro-absorption device[3] is also very efficient and has the advantage of small physical size. Its application is, however, limited to intensity modulation with limited linearity and with significant accompanying phase modulation (chirp); the operating wavelength range is also somewhat restricted. We anticipate therefore that for most microwave and millimeter wave applications the electro-optic devices will be preferred, particularly where a wide spurious-free dynamic range is an important requirement.

The total insertion loss of integrated optical modulators for millimeter wave operation is currently 6-12 dB (single mode fibre to single mode fibre), this range reflecting the choice of waveguide parameters and hence of the optical spot size within the modulator. In general, the lower interfacing losses are achieved with slightly larger modal diameters, resulting in higher V_π values for a given interaction length (the lowest insertion loss figures quoted here correspond to $V_\pi \approx 10$ V). Clearly a trade-off can be established to meet specific system needs. Further improvements in insertion loss may be expected in view of the rapid progress achieved in recent work.

High speed photodiodes
High speed photodetectors generally employ a p-i-n configuration[5] to enable the optimum trade-off between speed and quantum efficiency to be obtained. Our work has

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concentrated on high speed InGaAs/InP photodetectors for the 1.3-1.55 μm wavelength band using the substrate entry configuration, which substantially reduces the parasitic capacitance of the device since the entire junction area forms a usable optically active region[6]. We employ the flip-chip solder-bump bonding technique[7] to mount the device with the substrate side upwards; all of the electrical connections are made directly to a coplanar transmission line, thereby eliminating all bond wires (figure 3). The coplanar line is typically tapered along its length, in order to match the geometry of the diode to that of the connector.

The frequency response of the photodetector is determined by the transit time of the carriers across the depletion region and by the device capacitance in the external circuit. Detailed modelling of the structure has been carried out[8] in order to provide a basis for the optimisation of device parameters for specific requirements. This approach has allowed devices to be designed for operation up to 40 GHz without unduly limiting the active size: with an intrinsic width of 0.5-0.7 μm, an active diameter in the range 25-30 μm can be employed, making optical fibre alignment relatively straightforward[9].

A typical planar solder bonded device structure is illustrated in figure 4. The epitaxial structure is grown by low pressure MOVPE. In our PIN design the p-n junction is formed by a local area zinc diffusion through a silicon nitride mask, which is subsequently left in place to form a passivating layer. All contact metallisations are made to the epitaxial side of the device. The coplanar waveguide substrates are fabricated using conventional thin film processes. Provision is made for decoupling using either chip capacitors or integral thin film capacitors: the former have been found to limit the performance significantly above 20 GHz[8,9] and more recent work has accordingly concentrated on the monolithic decoupling option.

Conclusions

Optoelectronic devices are now available for the construction of efficient millimeter-wave optical links. GaAs integrated optical modulators based on a velocity-matched transmission line configuration which have been designed for bandwidths up to 40 GHz indicate considerable potential for higher frequency operation. The high modulation efficiency of these devices leads to modest drive power requirements which are compatible with solid-state sources. At the receive end of the link, high efficiency, wide bandwidth photodiodes are also available. The way is now open for designers to exploit the many advantages of optical transmission in ultra-wide bandwidth and millimeter-wave frequency systems.

Acknowledgments

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References

1. Walker, R.G., IEEE J. Quantum Electronics, March 1991.
2. Walker, R.G., Bennion, I. and Carter, A.C., Electron. Lett., **25**, pp. 1549-50 (1989).
3. Wakita, K., Kotaka, I., Mitomi, O., Asai, H., Kawamura, Y. and Naganuma, M., Conf. Lasers Electro-Optics, 1990, paper CTUC6.
4. Nees, J., Williamson, S. and Mourou, G., Appl. Phys. Lett., **54**, pp. 1962-64 (1989).
5. Bowers J.E., Burrus C.A. and McCoy R.J., Electron. Lett. **21**, pp. 812-814 (1985).
6. Sussman, R.S., Ash, R.M., Moseley, A.J. and Goodfellow, R.C., Electron. Lett., **21**, pp. 593-5 (1985).
7. Miller, L.F., IBM J. Res. Develop., 1969, pp. 239-250; Goodwin, M.J., Moseley, A.J., Robbins, D.J., Thompson, J. and Goodfellow, R.C., Proc. SPIE, **1215**, pp. 55-62 (1990).
8. Humphreys, D.A. and Moseley, A.J., IEE Proc., pt. J., **135**, pp. 146-152 (1988).
9. Moseley, A.J., Carter, A.C., Kearley, M.Q., Park, C.A. and Humphreys, D.A., Proc. SPIE, **995**, pp. 61-67 (1988).

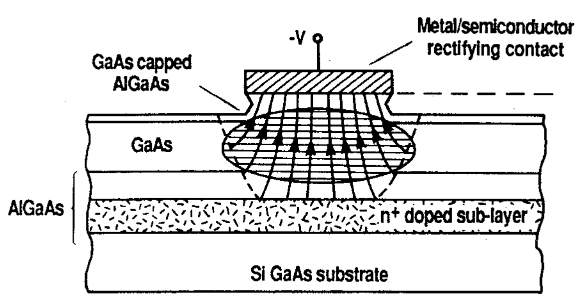

Figure 1. GaAs/AlGaAs electro-optic waveguide.

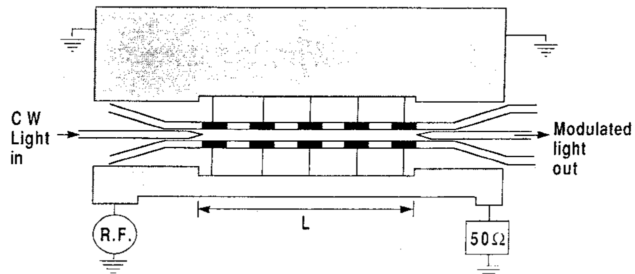

Figure 2. Loaded-line travelling wave modulator.

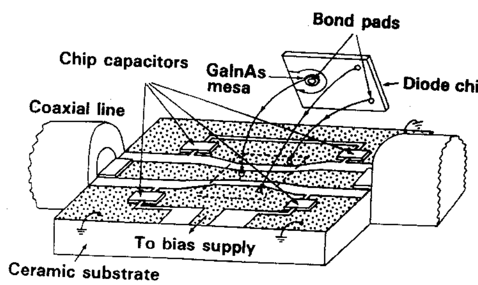

Figure 3. Schematic of flip-chip assembly of high speed photodiode chip on to a coplanar line.

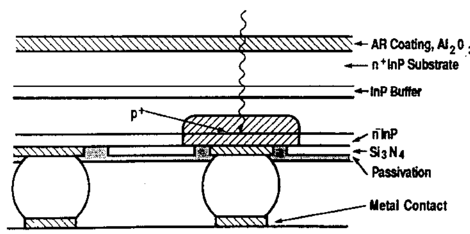

Figure 4. Cross-section of a planar InGaAs/InP photodiode chip for solder bond assembly.