Microwave Photonic Multichip Modules Packaged on a Glass-Silicon Substrate

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***Abstract*—A hybrid microwave photonic integration technology known as *optoelectronic glass microwave integrated circuit* (opto-GMIC) has been developed. It is a multichip module approach that uses a glass substrate on a silicon carrier to interconnect both discrete and monolithic microwave and optoelectronic devices. The glass substrate can support both lumped and distributed elements, thus reducing the number of parts in assembly. In addition, a wide variety of microwave photonic multichip module designs can be produced from the same production line. This has been demonstrated by the fabrication of prototype fiber-optic repeaters, transmitters, and receivers designed for synchronous optical network applications at a bit rate of 622.08 Mb/s and a wavelength of 1.3 μm.**

I. Introduction

The excellent transmission properties of optical fiber have led to its domination of long-haul telecommunications networks. This success has spurred the use of photonics for microwave applications such as CATV distribution. These applications are similar to long-haul networks in their use of relatively long spans of fiber and a low optoelectronic device count. Consequently, the cost is not dominated by fiber (which is a commodity product) but by the microwave photonic modules. This is not a burden in cases where the cost of a packaged high-speed laser, for example, can be shared by many subscribers. However, the emerging applications of fiber-to-the-home and computer interconnects will demand low cost and reliability in addition to high modulation speeds. While these problems have been solved at the chip level, they remain elusive at the packaging stage. Packaged photonic subsystems will have to be produced in large numbers and offer functionality (at the package level) beyond that of simple transmitters and receivers. These considerations will also apply to optically controlled phased array antennas and optically fed wireless communications.

Monolithic integration of photonic and microwave devices on a single chip has been proposed as a means of satisfying future demand for reduced cost and increased functionality. Despite some encouraging results [1], [2], optoelectronic integrated circuits (OEIC's) are more complex than MMIC's. They require planar and vertical structures, hence multistep wafer processing is necessary and this leads to high costs and low yields. In addition, an optimum OEIC material for electronic, optical, and optoelectronic functions has not been found. However, even if OEIC's were widely adopted, they would not eliminate the major cost factor in manufacturing: assembly, test, and *packaging*. The cost of pigtailed lasers is dominated by the active alignment of the fiber to the laser and not by the chip, regardless of whether it is a discrete device or an OEIC [3]. In contrast, hybrid optoelectronic integration [4] allows optoelectronic, optical, and electronic devices to be optimized separately in order to realize the best subsystem performance on a photonic multichip module (PMCM). Furthermore, optical fibers and microlenses can be passively aligned to optoelectronic devices. This has been demonstrated by using silicon as the supporting substrate [5]–[15]. The advantage of using silicon is the ability to anisotropically etch features such as V-grooves for fibers and to define optical waveguides using silicon dioxide [5]. There are also other incentives to use silicon for PMCM's, most of which are common to conventional MCM's. These include excellent thermal properties, mechanical stability, and a well-developed manufacturing base, which will reduce the investment required to establish production lines [16].

The microwave applications cited earlier will require microwave PMCM's (MPMCM). Gigabit transmitter modules on a silicon waferboard [8] and a microwave photonic transceiver for phased array interconnects [7] have been developed. However, neither module demonstrated a full capability for microwave signal processing. For example, the transmitter in [7] consisted of a 1.3-μm DFB laser coupled to a fiber with a ball lens, isolator, and GRIN lens. The laser and micro-optics were passively aligned through etched features on the silicon platform. However, the laser driver MMIC, along with the associated transmission lines and matching network, had to be accommodated on a separate alumina circuit.

This paper describes a microwave photonic multichip module technology known as opto-GMIC (optoelectronic glass microwave integrated circuit). Opto-GMIC can accommodate optical, optoelectronic, and microwave components, along with passive matching and bias networks on a *single* glass-silicon platform. In Section II, the opto-GMIC concept is explained. The feasibility of this technology is then examined through the fabrication (Section III) of prototype circuits designed for synchronous optical network (SONET) applications. Preliminary tests on the prototypes were reported in [17]; additional and improved results are presented in Section IV.

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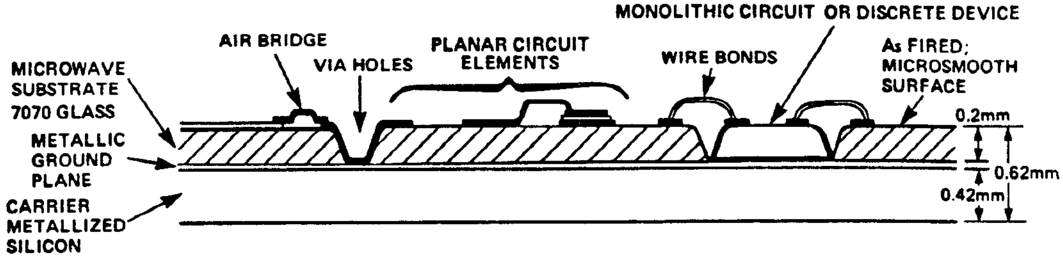


Fig. 1. GMIC cross-section illustrating the interconnection of semiconductor devices with monolithically defined passive elements.

II. Opto-GMIC Technology

Opto-GMIC is an evolution of GMIC technology [18]. GMIC was originally developed as a highly reproducible fabrication technology for a broad range of hybrid microwave circuit applications and as an integration medium for multichip MMIC designs. Fig. 1 illustrates a cross-section of a typical GMIC. The glass layer serves as the microwave dielectric, while the silicon layer provides the necessary mechanical support and creates an integral carrier. A gold film between the two carries the ground currents to minimize losses. Semiconductors can be mounted to the silicon through holes in the thin glass layer. Unlike MIC fabrication, GMIC offers a high level of integration of passive elements, including: deposited thin-film capacitors (0.2–80 pF range); photolithographically defined plated via holes for groundplane access and semiconductor device mounting; airbridge interconnections for DC/DC, RF/DC, and RF/RF crossings; thin-film resistors generated from a tantalum nitride process (5–10 kΩ range); and spiral inductors (1–15 nH range).

Corning 7070 glass was chosen as a microwave substrate material for four important reasons [18]. It has low loss at microwave frequencies (loss tangent below 0.002), a good thermal expansion match with silicon (expansion coefficient of 3.2 ppm/°C), can be etched (to form via holes), and has a low dielectric constant (4.1). The last property supports a broad range of characteristic impedance values (35–150 Ω) on an unusually thin substrate (0.2 mm). A thin substrate has several advantages. First, semiconductors can be mounted to the underlying silicon carrier without the use of pedestals; via holes can be chemically etched with better accuracy in thin material; and finally, the parasitic inductance of via hole ground connections is reduced. Although the thermal conductivity of the glass is low (0.011 W/cm°C), this is not a hinderance, as semiconductors are die attached directly to the silicon.

The role of silicon in GMIC is primarily twofold. It provides rigid mechanical support to the thin glass substrate, and it provides good thermal conductivity (1.3 W/cm°C) for efficient heat transfer. However, silicon also possesses numerous other properties that make it a fortuitous choice for MPMCM's. These include low cost, excellent flatness and smooth surface finish, and compatibility with thin-film processing methods (especially sawing for final circuit separation). The availability of silicon in wafers also provides a significant advantage in manufacturing, since the GMIC wafer can be handled with the same cassette-to-cassette processing equipment used in the silicon IC industry.

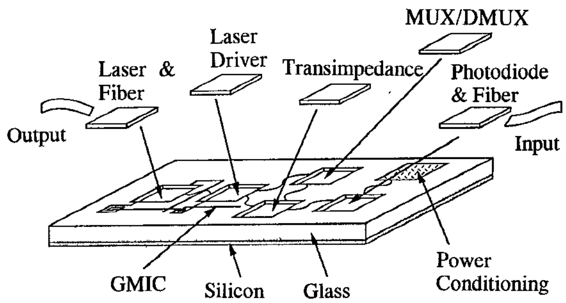


Fig. 2. Opto-GMIC transceiver concept.

Although GMIC has been developed for microwave circuit applications, it was realized that the composite glass and silicon substrate could be adapted for use as a MPMCM. The following features were identified as necessary for a fully developed MPMCM technology: 1) Passive electronic interconnection of microwave devices with one another and with optoelectronic devices on a single substrate. This is already possible with the standard GMIC process. Flip-chip bonding of devices is advantageous [15], and GMIC can support this technique; 2) insertion of micro-optical components and passive alignment [14] of optical fibers to optoelectronic devices; and 3) passive optical interconnection of optoelectronic devices with optical waveguide structures.

At present, a MPMCM with all these features has not been developed. For example, silicon optical bench [6] can support optical waveguide fabrication and fiber alignment V-grooves, but it makes no provision for interfacing to microwave devices. Silicon waferboard [8] also features passive alignment of laser diodes to optical fiber with silicon V-grooves, but it cannot support optical waveguide fabrication at present. Opto-GMIC, on the other hand, is an extended version of GMIC that has already demonstrated the first two features in the above list of requirements. These have been identified as being essential to the integration of laser diodes and photodiodes with their respective processing electronics. Transmitter, receiver, and receive/transmit modules will be vital to the implementation of fiber-in-the-loop for example. The existing GMIC foundry has been used to fabricate an optoelectronic transceiver and transmitter and receiver circuits. This has been achieved by incorporating laser diodes and photodiodes into via holes and

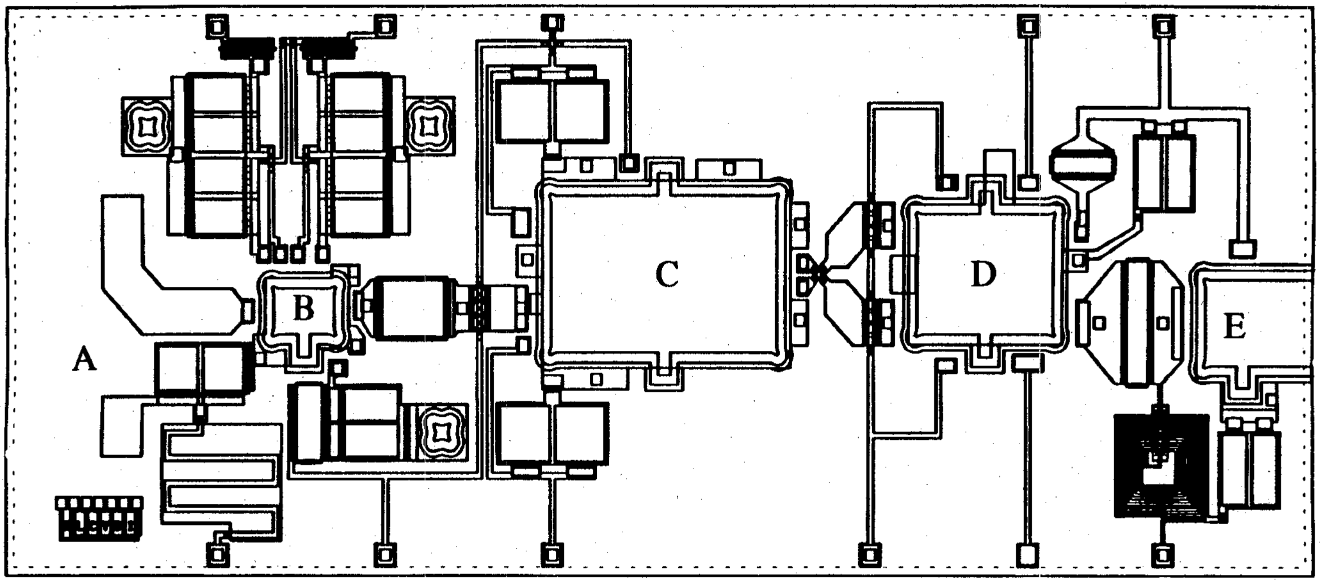


Fig. 3. Opto-GMIC transceiver layout. Overall dimensions are 13.2 mm by 5 mm. The photodiode is mounted at location A. The letters B, C, D, and E denote via holes for the transimpedance amplifier, limiting amplifier, laser driver, and laser diode, respectively.

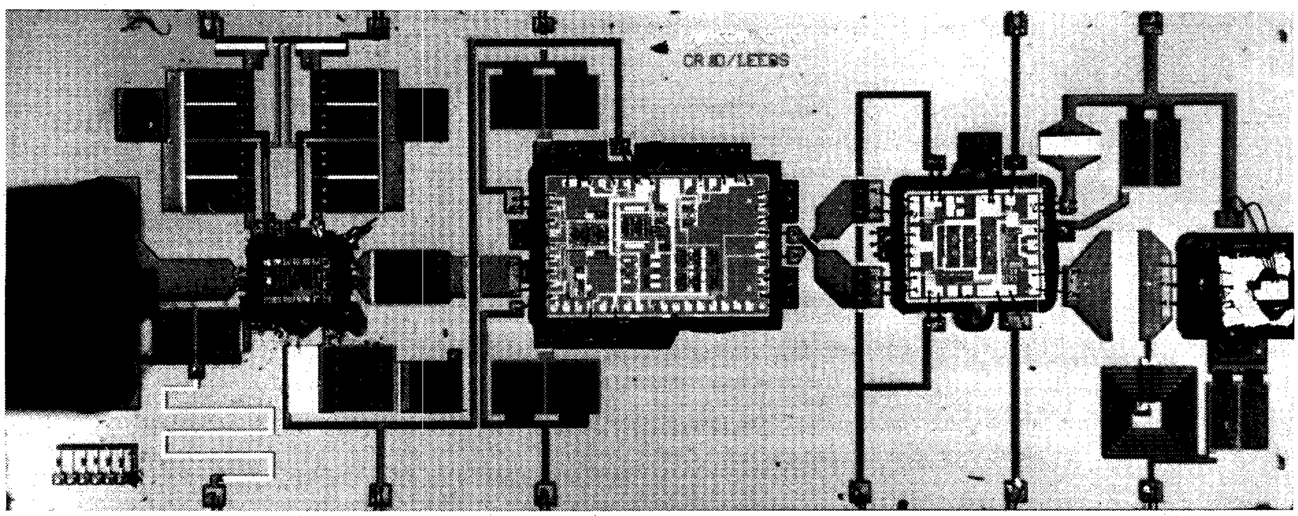


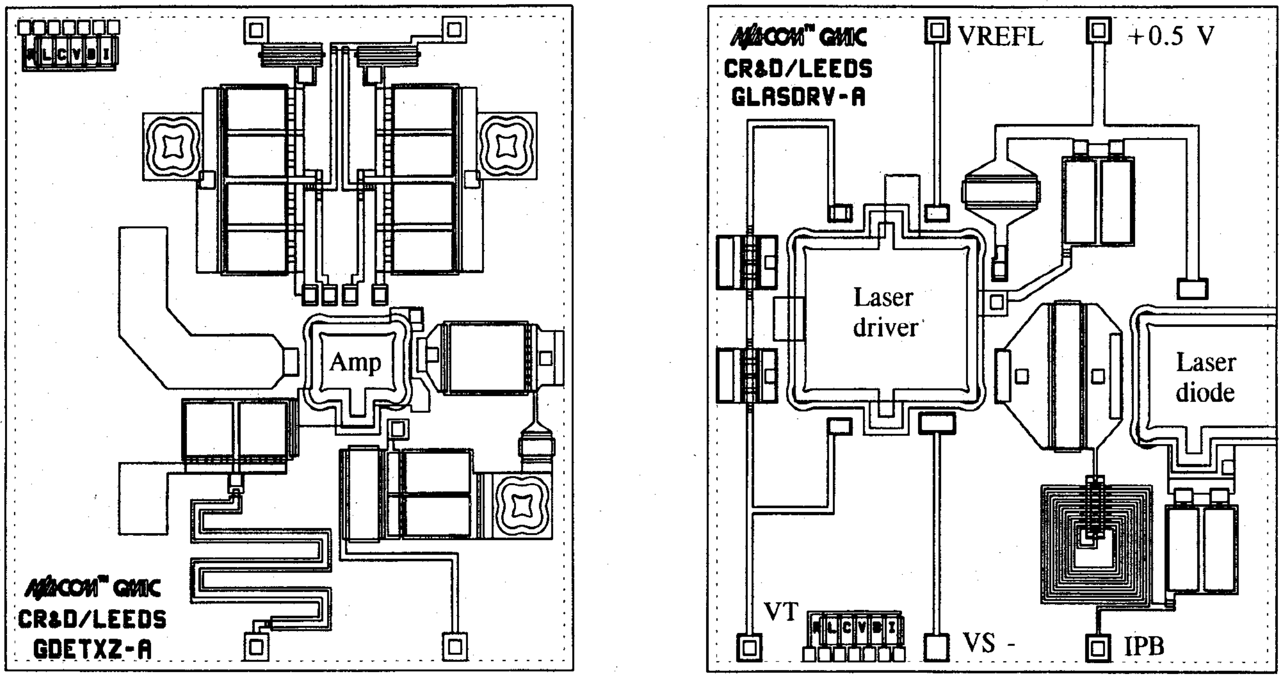
Fig. 4. Fully assembled opto-GMIC transceiver.

then interconnecting them with their associated MMIC circuits. Hence opto-GMIC offers the full electronic functionality of the GMIC process. A conceptual diagram of an opto-GMIC transceiver module is shown in Fig. 2. In addition, rudimentary fiber alignment grooves have been fabricated on a separate evaluation circuit with no modifications to the GMIC foundry. At present, optical waveguides have not been demonstrated in opto-GMIC because this feature was regarded as the least important.

It should be noted that the opto-GMIC prototypes have used an *appropriate level of integration*. The high electronic device count makes the use of GaAs MMIC's worthwhile, but there is no incentive to include the small number of lasers and photodiodes in a monolithic implementation. On-chip customization is highly expensive unless large volumes are produced and sold, and it is particularly wasteful to include passive elements on a monolithic chip when these components could be realized on the multichip carrier. On the other hand, a hybrid integration technique can passively interconnect inexpensive commodity chips. The advantage of this approach is that a single production line can accommodate designs of varying complexity and disparate production runs.

III. Opto-GMIC Prototypes

In order to prove the feasibility of the opto-GMIC concept, optoelectronic transmitter, receiver, and transceiver (repeater) circuits were fabricated using the standard GMIC foundry process. The original specification called for an optoelectronic transceiver to be designed to operate at the SONET OC-12 bit rate of 622.08 Mb/s and a wavelength of 1.3 μm. Fig. 3 shows the layout of the system. AT&T's FORCE 2.5 chip set was



(a) (b)

Fig. 5. Layouts for (a) photodetector module and (b) transmitter layout. Overall dimensions are 5 by 4.8 mm for both.

chosen as the basis of the transceiver design. The photodiodes are BT&D InGaAs p-i-n devices mounted in a low ceramic block. The laser diode chips are based on BT&D InGaAsP buried heterostructure technology and emit in the 1270–1330 nm wavelength range. These were mounted p side down onto a silicon carbide heatspreader, which was directly bonded to the silicon layer of the opto-GMIC. A photograph of a fully assembled opto-GMIC transceiver circuit is shown in Fig. 4.

"Pull-out" circuits were also developed. These comprise the photodetection, limiting, and transmitting submodules of the transceiver. In other words, the photodetector pull-out layout corresponds to the photodetector and transimpedance amplifier blocks of the transceiver; the limiting amplifier pull-out contains the limiting amplifier block only; and the transmitter pull-out consists of a laser driver and laser diode. Layouts for the transmitter and receiver circuits are shown in Fig. 5. The opto-GMIC's and their associated microstrip bias and RF supply circuits were mounted in brass fixtures. By using an opto-GMIC implementation, the bond wire count was kept to a minimum. SMA microstrip launchers were used for the RF connections, while the optical interface was achieved by positioning single-mode optical fiber with submicron precision XYZ stages.

The fabrication of fiber alignment grooves in opto-GMIC glass was examined with a dedicated circuit. By varying the opto-GMIC via width, it was postulated that the fiber could be attached by three methods. In the first, the opto-GMIC via approximates a conventional silicon V-groove and the silicon side of the opto-GMIC via is redundant. The second width is such that the fiber can be gently "snapped" into place and held securely, while the last width allows some clearance for the fiber to rest on the silicon. Fig. 6 is a photograph of a fabricated fiber via circuit; the width of the largest via is about

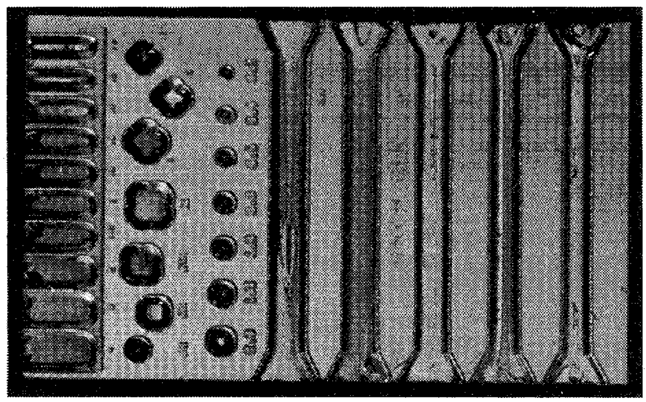


Fig. 6. Fabricated fiber via circuit. Overall dimensions are 3 by 5 mm.

290 μm while that of the smallest is 220 μm, hence primary coated single-mode fibers can be inserted into the grooves and epoxied in place.

IV. Results

A. Fiber Via Circuit

The via circuit was tested in the fiber-to-fiber coupling application. Two cleaved single-mode fibers (overall diameter 250 μm) were inserted into either side of the via whose width was marginally larger than 250 μm. By using this via, the lateral movement of fibers was restricted so that the groove provided self alignment of two axes. Using precision micromanipulators, the fibers were brought into close proximity and aligned in order to minimize insertion loss due to Fabry–Perot interference. A laser diode transmitted 7.3 dBm of optical power into the first fiber, and the power coupled into the

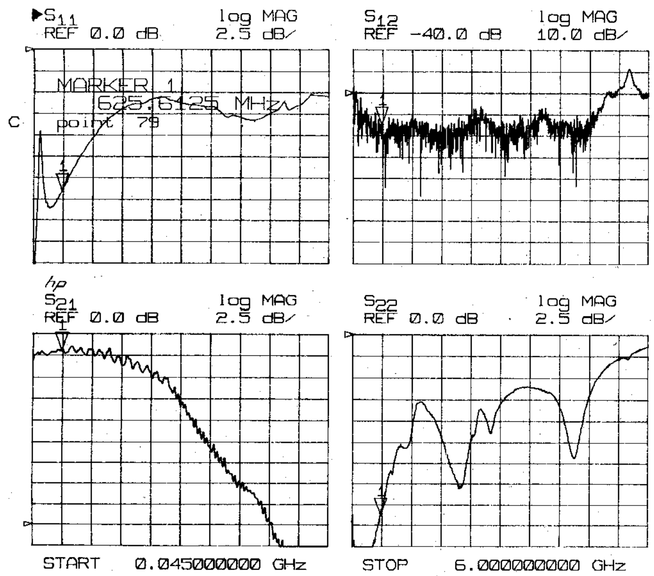


Fig. 7. Measured S-parameters of limiting amplifier pull-out.

second was monitored with a power meter during alignment. A best-case result of 1.9 dB fiber-to-fiber coupling loss at a wavelength of 1.3 μm was observed when the fibers were butt coupled.

B. Limiting Amplifier

Fig. 7 shows the measured S-parameters of the complete fixture measured on an HP 8510 C network analyzer calibrated with an open-short-load technique. A bias voltage of −6 V was used and a power level of −10 dBm was applied to the test ports. The packaged GMIC small-signal S-parameters meet the specifications quoted for the limiting amplifier at the design frequency of 622 MHz. At this frequency the small-signal gain exceeds 20 dB and the input and output return losses are both better than 15 dB.

C. DC Characterization of Laser Diode and Photodiode on Opto-GMIC Transceiver

A semiconductor parameter analyzer (HP 4145A) was used to examine the DC characteristics of the laser diode and photodiode mounted on the transceiver circuit. Fig. 8 depicts the I–V characteristic measured at the +0.5 V probe. The path from this probe to ground includes the laser diode and resistance due to the bias elements on the opto-GMIC. Hence Fig. 8 has the same form as the laser diode forward voltage versus forward current characteristic, but the threshold voltage is shifted by approximately 2–3 V. Fig. 9 shows the reverse bias characteristics for the transceiver measured at the photodiode probe. In this case, the path to ground includes the photodiode and a 10 kΩ resistor in series, hence the I–V characteristic closely resembles that of the photodiode alone. The breakdown below −42 V can be clearly seen.

D. Characterization of Photodetector and Laser Transmitter

The RF performance of the photodetector opto-GMIC was investigated as follows. A high-speed pigtailed laser transmitter (Ortel 3541B-001) emitting 3 mW of optical power at a wavelength of 1.31 μm was modulated at a frequency of 622 MHz. The output from the laser pigtail was then butt coupled to the photodiode submount of the photodetector circuit, while the RF output was monitored on a microwave spectrum analyzer (HP 8562A). Fig. 10 shows the output RF spectrum of the opto-GMIC photodetector module with a 3 dBm input to the test laser. Greater output powers could be achieved if the optical coupling was improved by using a tapered fiber or a gradient-index rod lens, for example.

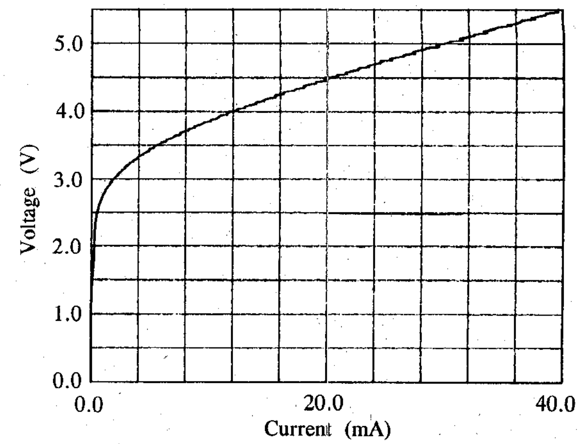


Fig. 8. VI curve obtained at laser offset voltage probe of the transceiver.

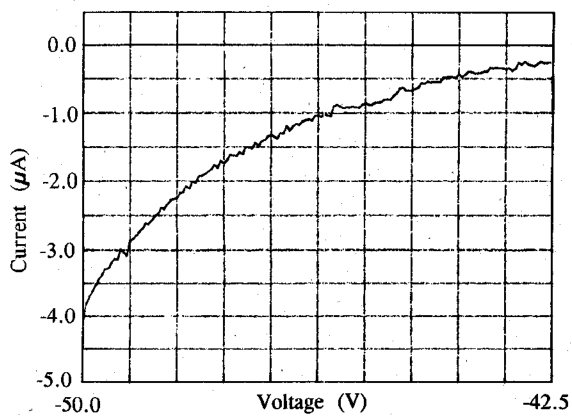


Fig. 9. Reverse voltage characteristics of photodiode section of transceiver.

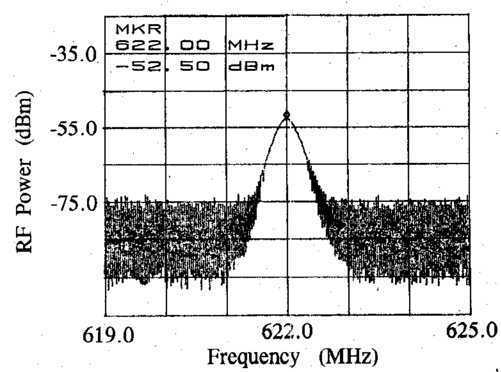


Fig. 10. RF output spectrum of photodetector pull-out with 3-dBm input to test laser.

At the time of writing, microwave measurements on the laser transmitter were in progress. However, active alignment of the transmitter to single-mode optical fiber has been demonstrated. With the prebias current of the laser chip on the transmitter opto-GMIC set to 50 mA, 0.58 mW of optical power was coupled into a single-mode optical fiber. At this bias, the manufacturer's data sheet indicates that the laser chip emits 5 mW. Hence, this result indicates a coupling efficiency of approximately 11%, which compares very favorably with accuracies achieved with other transmitters [8]. The coupling efficiency could be increased further by using tapered fiber. It is also possible, in a future design, to include fiber alignment grooves on the opto-GMIC itself (as demonstrated above) in addition with alignment posts for the laser chip. Vias for micro-optic lenses may also be possible. This would then permit passive alignment of fibers to laser diodes.

V. Conclusion

Hybrid integration of microwave and photonic devices on a single multichip module has been demonstrated. This approach allows lumped and distributed passive elements to be incorporated on such a module for the first time. Moreover, the feasibility of including fiber alignment grooves for passive alignment to optoelectronic devices has been shown to be feasible. Opto-GMIC therefore represents a photonic-microwave multichip module technology that has excellent microwave functionality and can ultimately allow for cost-effective inclusion of optical components. Optical coupling and RF tests have proven the validity of this interconnection technique. While the RF results have been presented at a frequency of 622 MHz, it should be pointed out that opto-GMIC can support microwave circuits (and, by inference, high-speed optoelectronic devices) that operate at frequencies as high as 18 GHz. Hence opto-GMIC is potentially an extremely cost-effective means of producing many different microwave photonic multichip module designs using a single foundry.

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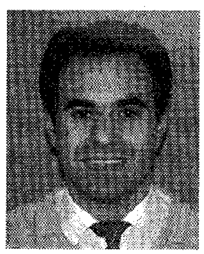

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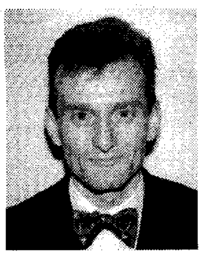

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After graduating, he joined the University of Leeds Industrial Services Unit as a consultant to B.Ae. (Dynamics) designing, fabricating, and testing InP-based diodes. In October 1991, he joined M/A-COM's Corporate R&D Center where he is responsible for semiconductor materials research and processing. His specific assignments have included integration of InP-based optical devices into M/A-COM's glass technology and InP-based device development. His current interests are concerned with flip-chip processes for efficient thermal management of HBT power amplifiers, development of InP based HBT's, and the UHV-CVD growth of SiGe epitaxy for SiGe HBT's.

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After graduating in 1977, he worked as an Applications Engineer for Mullard, Mitcham. In 1982, he was appointed Lecturer in the Department of Electronics at the University of York. He joined the Microwave Solid State Group in the Department of Electronic and Electrical Engineering at the University of Leeds in 1983, where he currently holds the Chair of Professor of Microwave Engineering. He is currently Head of the Department of Electronic and Electrical Engineering at the University of Leeds. During 1987, he was a Visiting Research Associate at the California Institute of Technology. He has been a Consultant to M/A-COM Inc., Corporate Research and Development since 1989, where he was on sabbatical leave during the period 1990–1991. During this year, he represented M/A-COM as Senior Staff Scientist. His main research interests include compound semiconductor device modeling, microwave, terahertz and optical nonlinear subsystem design, and advanced semiconductor devices. He has written seven books and more than 130 papers. He is a Member of the MIT Electromagnetics Academy.

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