Single-MMIC Four-Channel Transmitter Module for Multichannel RF/Optical Subcarrier Multiplexed Communications Applications

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***Abstract*—We present a compact single monolithic microwave integrated circuit (MMIC) transmitter module for four-channel RF/optical subcarrier multiplexed (OSCM) communication applications. The developed module consists of one fully monolithic four-channel OSCM transmitter integrated circuit (IC) and four coupled-line filters. The MMIC is designed and implemented in a commercial 0.6-μm GaAs MESFET process and five-stage coupled-line filters are fabricated for each of the four channels on the module board. We present the module design and bit-error-rate performance. This is the first fully monolithic IC transmitter module for OSCM communications applications.**

***Index Terms*—Bandpass filters, MMIC mixers, MMIC oscillators, MMICs, MMIC transmitters, optical communication, subcarrier multiplexing, voltage-controlled oscillators.**

I. Introduction

DUE TO THE large available bandwidth of fiber-optic networks, multichannel communication can be supported over the fiber using wavelength division multiplexing (WDM) [1], optical subcarrier multiplexing (OSCM) [2] and combination WDM–OSCM techniques [3], [4]. These multichannel multiplexing techniques allow the network interface electronics to be operated at the individual channel rate [5]. An important issue in optical packet switched networks is packet coding and addressing. There are many techniques to communicate control information in a WDM optical network including in-band signaling [6], out-of-band signaling on a separate control wavelength [7], and OSCM [3], [5]. Two main advantages of an OSCM are: 1) an OSCM link requires only one terminating element, such as a distributed feedback (DFB) semiconductor laser and a photodetector at each node and 2) an OSCM supports simple detection of control channels that carry control or timing information. However, one major problem is the complexity and cost of the electronics.

The developed four-channel OSCM transmitter module consists of one fully monolithic integrated circuit (IC) and four coupled line bandpass filters without any off-chip discrete components. The developed module is capable of generating four subcarriers with approximately 500-MHz spacing and supports up to 50 Mb/s of data per channel. The designed fully monolithic IC consists of four voltage-controlled oscillators (VCOs), each with a buffer amplifier, which can cover a frequency range of 3.8–5.5 GHz for subcarrier generation and four modulators for on–off keying (OOK) subcarrier modulation. Implementation of multichannel OSCM interfaces in monolithic technology is very important because it provides circuit simplicity with improved reliability, decreased size, lighter weight, and reduced manufacturing cost compared to using hybrid technology. In addition, monolithically integrated devices have much less parasitic reactance than discrete packaged devices. Circuit flexibility and performance can also be enhanced with little additional cost since it is very easy to fabricate additional FETs in a monolithic microwave integrated circuit (MMIC) design. The coupled line filters are fabricated on the module board to reduce interchannel crosstalk, to suppress harmonics and spurious signals, and to reject baseband feedthrough.

In this paper, we present the first fully monolithic four-channel OSCM transmitter IC design in the TriQuint TQTRx 0.6-μm GaAs MESFET process, as well as the corresponding module development. The developed module is fully characterized and its feasibility is demonstrated with bit-error rate (BER) measurement results using four 50-Mb/s pseudorandom bit sequences (PRBSs) as channel input data. This work can contribute to solving major issues of the complexity and cost of multichannel OSCM communications link by leveraging low-cost GaAs MMIC technology.

II. Module Design

As illustrated in Fig. 1, the developed transmitter module consists of one MMIC and four 250-MHz coupled-line bandpass filters on a 2 in $\times$ 2 in $\times$0.025 in ceramic substrate without using any off-chip discrete components. Eight SMA connectors are used for four output ports and four control-channel data-input

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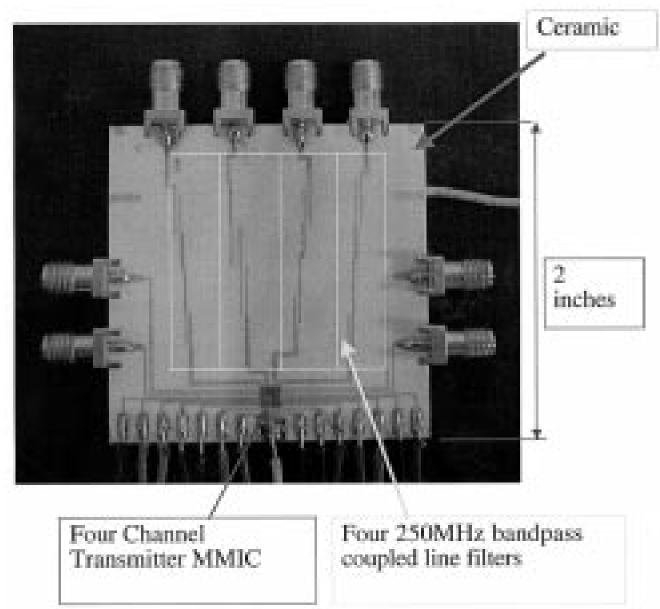

Fig. 1. Four-channel single-MMIC transmitter module.

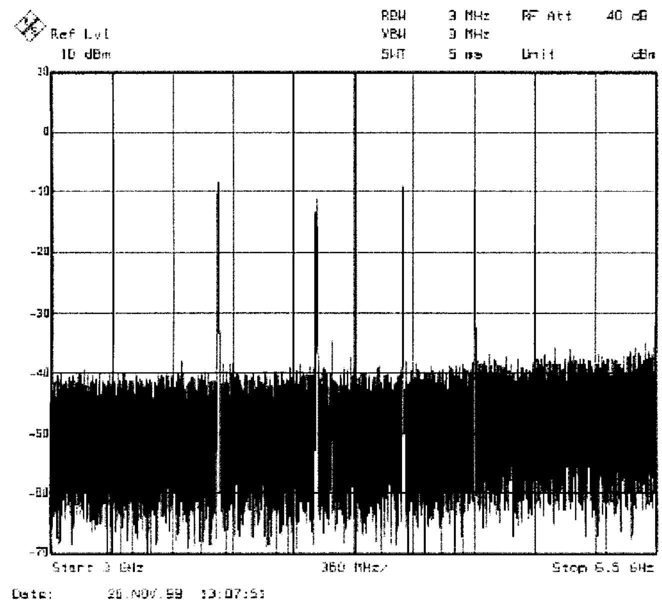

Fig. 2. Output spectrum of an SCM module with no modulation.

TABLE I
DC-BIAS CONDITION FOR TRANSMITTER MCM

	Voltage [V]	Current [A]
Buffer amp drain supply for A,B,C,D	3.00	0.12
Buffer amp gate supply for A,B,C,D	-0.90	0.00
VCO drain supply for A	4.50	0.06
VCO drain supply for B	2.85	0.04
VCO drain supply for C	2.40	0.04
VCO drain supply for D	5.50	0.03
Control supply for A	0.85	0.00
Control supply for B	2.40	0.00
Control supply for C	4.40	0.00
Control supply for D	5.65	0.00

TABLE II
SCM OUTPUT FREQUENCIES AND POWERS

	Frequency [GHz]	Power [dBm]
Subcarrier Channel A	4.00	- 8.0
Subcarrier Channel B	4.55	-11.0
Subcarrier Channel C	5.05	- 9.0
Subcarrier Channel D	5.45	- 9.5

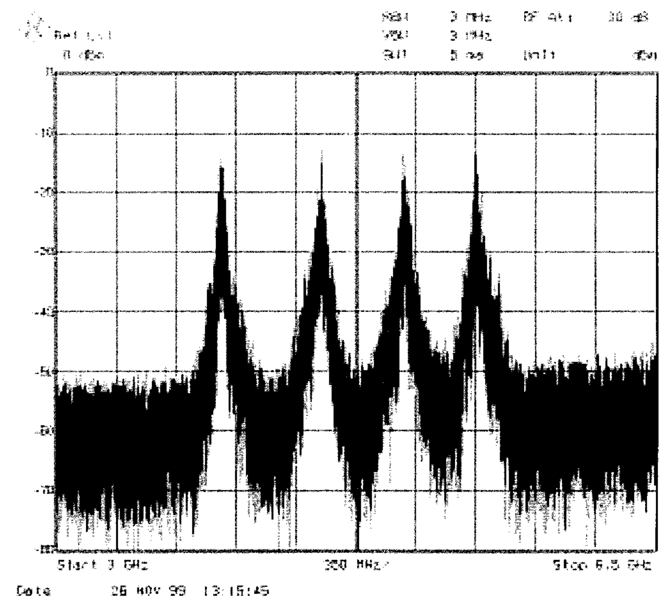

Fig. 3. Modulated output spectrum of an SCM module with 50-Mb/s data.

ports. Ten wires are also used for dc-bias controls. DC-bias conditions are shown in Table I. This module generates four subcarrier frequencies at 4.00, 4.55, 5.05, and 5.45 GHz, as summarized in Table II. The measured output spurious and harmonic signals are less than −25 dBc. Four data inputs up to 50 Mb/s can be used to modulate the four RF subcarriers on the module. The MMIC is mounted on the board using silver epoxy and wirebonds. Modulated and nonmodulated output spectrums are shown in Figs. 2 and 3.

III. MMIC DESIGN

The fully monolithic four-channel OSCM transmitter IC consists of four VCOs, four buffer amplifiers, and four OOK modulators in 120 $\times$ 120 mil^2 die, as shown in Fig. 4. All the functionality of the six MMIC chipsets used in a four-channel MMIC-based multichip OSCM transmitter module [7] has been combined into a fully monolithic IC. DC power consumption has also been reduced by over 50% from 2.1 W of the multichip module (MCM) [7] to 1 W. The designed MMIC has been fabricated using the 0.6-μm TriQuint semiconductor TQTRx MESFET process. The fully monolithic implementation is critical due to great advantages over multichip solutions in terms of cost, size, interconnect losses, reliability, and ease of integration.

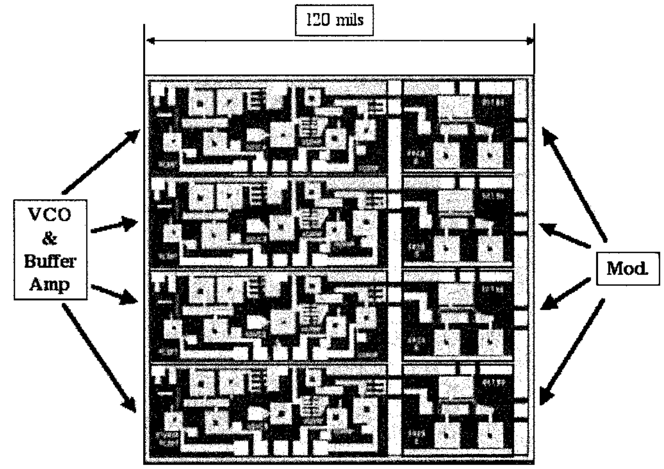

Fig. 4. Four-channel OSCM transmitter MMIC.

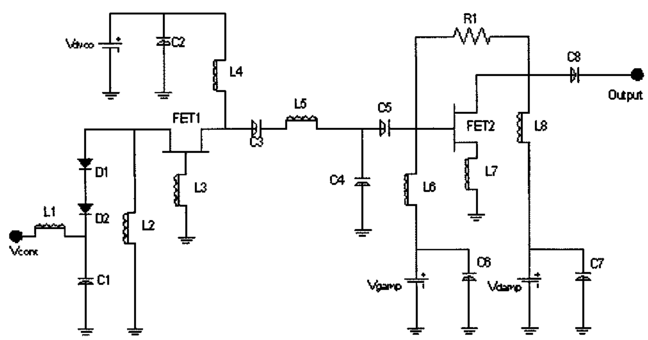

Fig. 5. VCO schematic.

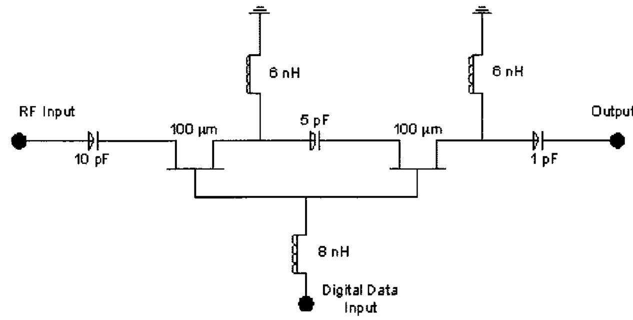

Fig. 6. Schematic of OOK Modulator.

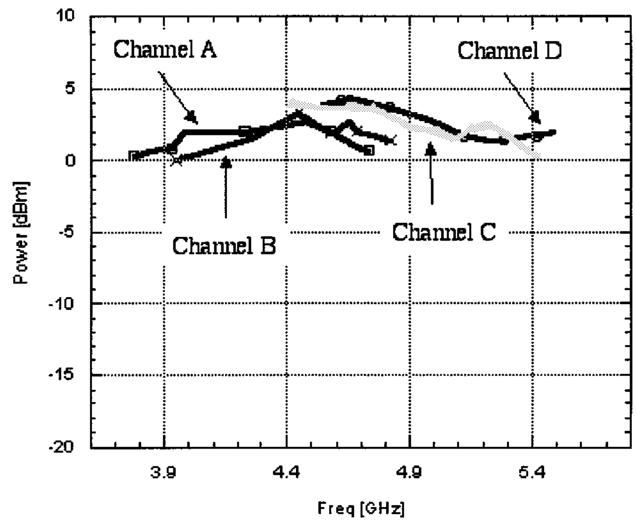

Fig. 7. MMIC output power versus frequency for each channel.

All four VCOs have a common-gate single-FET topology with a varactor diode at the source for frequency tuning, as shown in Fig. 5. Each of the four VCOs are designed to cover a different frequency range to have a wide overall frequency tuning range. This wide-frequency tuning range allows support of over four channels for the OSCM link applications by using multiple MMIC chips. Depletion-mode MESFETs (DFETs) and n^+ overlap diodes have also been used for the active devices and the varactor diode, respectively. Bias networks for the DFET and varactor are designed on-chip to eliminate the use of any off-chip passive components.

The buffer amplifier is designed to facilitate better output matching and desensitize the VCO from changing external load impedance between the on and off states of the succeeding OOK modulator. A simple single-stage common source class-A resistive feedback depletion MESFET amplifier is used for the buffer amplifier design. LC matching circuits are used for matching both input and output with on-chip bias, which is also used as part of the matching circuit.

The modulator is a key component in upconverting the digital data onto the subcarrier. The OOK MMIC modulator consists of two GaAs MESFET switch-type FET mixers, which make use of the gate bias dependence of the FET's channel resistance in series, as shown in Fig. 6. The FET is used as a passive device and no drain bias is needed. Hence, the dc power dissipation will be miniscule. This FET mixer topology provides low $1/f$ noise and low unwanted intermodulation product for high RF drive levels [8] and good inherent isolation between the gate and source, as well as between the drain and source in the off state. The series configuration switch has been chosen to achieve frequency independent insertion loss. A 100-μm gatewidth DFET is used for the modulator design to balance the needs of isolation and power-handling capacity. Two DFET switches are cascaded to improve the extinction ratio. The LC matching is used to improve the output matching of the modulator. The digital data input is applied to the gate to OOK modulate the RF subcarriers generated by the VCO in the same channel. For the gate bias circuit, a large series inductor is used to provide an effective RF open to the FET at the gate terminal.

TABLE III
MMIC OUTPUT FREQUENCIES TUNING AND POWER RANGES

	Frequency Tuning Range[GHz]	Power Range [dBm]
Channel A	3.78 ~ 4.73	0.33 ~ 2.67
Channel B	3.95 ~ 4.82	0 ~ 3.33
Channel C	4.42 ~ 5.42	0.17 ~ 4.33
Channel D	4.55 ~ 5.48	1.33 ~ 3.83

IV. MMIC CHARACTERIZATION

All four channels of the MMIC have been fully characterized. As shown in Fig. 7 and summarized in Table III, the frequency tuning range of approximately 900 MHz with an output power

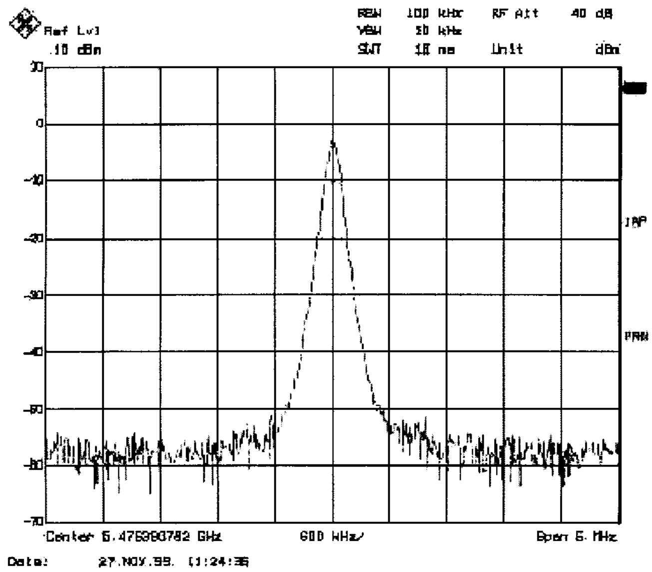

Fig. 8. Phase noise of subcarrier generated form the module.

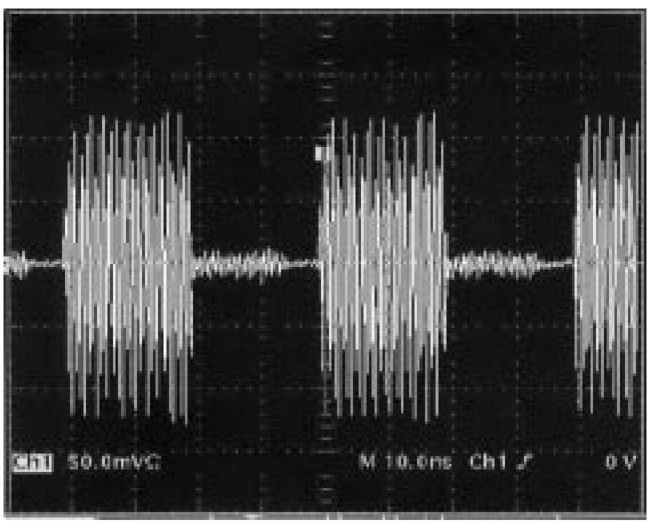

Fig. 9. OOK modulator output from oscilloscope with a 50-Mb/s PRBS data input.

of 2±2 dBm has been measured for each individual channel, while the OOK modulator in the on state with harmonic output less than −15 dBc. The phase noise is measured to be less than −105 dBc/Hz at 1-MHz offset, as shown in Fig. 8. With an input data stream of a 2-V peak-to-peak 50- and 200-Mb/s PRBS, the conversion loss and extinction ratio are measured to be approximately 7.2 and 20.5 dB, respectively, as shown in Fig. 9 and Table IV. The input 1-dB compression point of the modulator is 9 dBm, which can be calculated from Table IV.

V. Filter Design

As shown in Fig. 1, four 250-MHz bandwidth five-stage coupled-line filters are designed on the module board to reduce interchannel crosstalk between closely spaced modulated subcarriers, to suppress harmonics and spurious signals, and reject baseband feedthrough. These filters are designed using the Microwave Design System (MDS) and Momentum 2.5-D Electromagnetic Simulator. Filters are fabricated on a 2 in × 2 in× 0.025 in ceramic substrate with 4.5-μm-thick gold trace. The center frequencies of four filters are at 3.98, 4.48, 4.96, and 5.42 GHz. Loss in the passband was 3.5±1 dB and return loss is less than −9 dB, as shown in Figs. 10 and 11.

TABLE IV
OOK Modulator Conversion Loss and Extinction Ratio Versus RF Input Power

RF Input Power [dBm]	50Mb/s Data Input		200Mb/s Data Input	
	Conversion Loss [dB]	Extinction Ratio [dB]	Conversion Loss [dB]	Extinction Ratio [dB]
-5	7.22	20.54	7.22	20.54
0	7.24	20.93	7.13	21.04
5	7.15	20.00	7.15	20.00
8	7.99	20.81	8.00	20.80
9	8.10	20.36	8.10	20.36

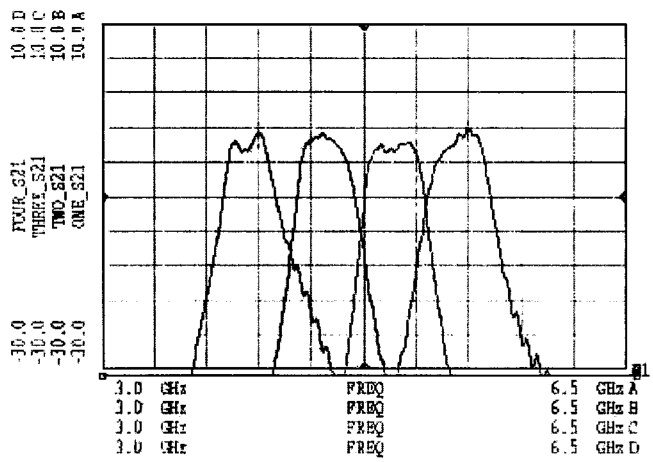

Fig. 10. Transmission measurement results of four filters.

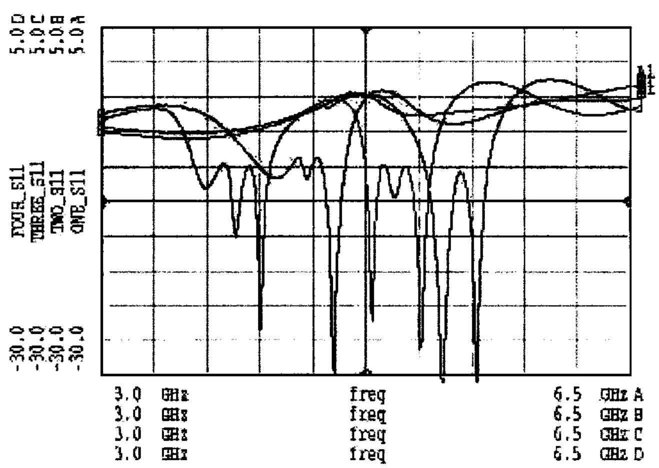

Fig. 11. Filter-input return-loss measurement results of four filters.

VI. Measurement Link Setup

Using the developed single-MMIC OSCM transmitter module, a four-channel back-to-back and a complete OSCM link BER measurement have been performed. The OSCM

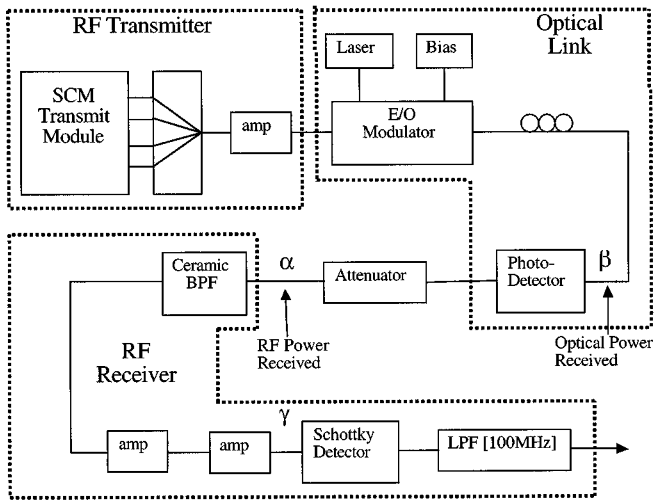

Fig. 12. Complete OSCM link measurement setup.

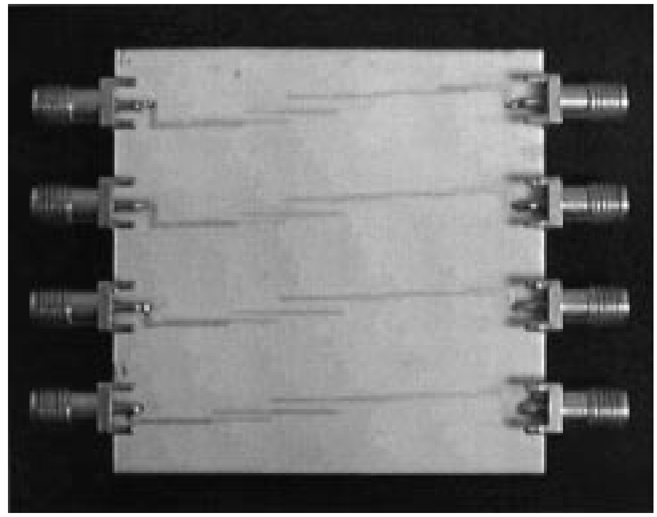

Fig. 13. Developed channel-selection filters.

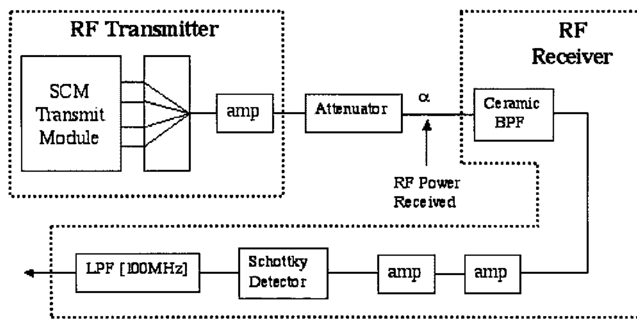

Fig. 14. Back-to-back measurement setup.

link setup consists of the RF transmitter, optical link, and RF receiver, as shown in Fig. 12. The RF transmitter consists of the developed four-channel transmitter module, a power combiner, and an amplifier. The developed module is used to generate four subcarriers and OOK modulate each of four 50-Mb/s data inputs with each subcarrier. A 4-to-1 power combiner and a 10-dB gain amplifier are used to combine and amplify four subcarrier channels. The optical link consists of a DFB laser, optical fiber, an electrical-to-optical (E/O) modulator, and an optical-to-electrical (O/E) detector. The combined four-channel output of the RF transmitter gets converted to an optical signal by intensity modulation of a 1550-nm wavelength DFB laser diode with an $LiNbO_3$ Mach–Zehnder (MZ) interferometer E/O modulator. The optical signal is transmitted through the optical fiber and is then converted back into an electrical signal using an O/E photodetector. To reduce the network and receiver complexity of the optical link, a direct detection scheme is used for O/E conversion. The RF receiver consists of a channel-selection filter, two amplifiers, and an electrical demodulator to retrieve information for each channel. For channel selections, four seven-stage coupled-line bandpass filters are designed and fabricated on a separate 2 in $\times$ 2 in $\times$ 0.025 in ceramic board, as shown in Fig. 13. Two amplifiers with a combined gain of 29 dB are used for signal amplification. The Schottky envelope detector is used with 100-MHz low-pass filter for demodulation of each channel to reduce receiver complexity associated with a coherent detection scheme that requires a phase locking of receiver subcarrier to the transmitter subcarrier.

The back-to-back link setup consists only of the RF transmitter and RF receiver, as shown in Fig. 14. The combined four-channel output signal generated from the RF transmitter gets directly fed into the RF receiver. The back-to-back link measurement is performed to show the performance of the developed four-channel transmitter module and receiver setup and to measure the power penalty caused by insertion of the optical link.

BER measurements have also been done with only a single active channel at a time in both back-to-back and complete OSCM link setups. These four single-channel BER measurements have been performed to show power penalty of a four-channel OSCM link using the developed module.

VII. RESULTS

The performance of the four-channel transmitter module is measured with back-to-back and complete OSCM link BER tests with 1×10^{11} b. All four channels are driven independently with 50-Mb/s PRBS data with a 2-V peak-to-peak amplitude generated from three arbitrary waveform generators (AWGs) and a BER tester. The BER performances of both links are measured versus received RF power at the point α shown in Figs. 12 and 14. For both of the back-to-back and complete OSCM links, received RF power is varied using electrical attenuators. All BER measurement results with all four channels active are plotted in Fig. 15. The BER performances of the complete OSCM link is also measured versus received optical power at the point β shown in Fig. 12 and plotted in Fig. 16. Received RF power is varied using an optical attenuator placed in front of the photodetector. For the logarithmic scale, 0 BER is replaced with a 1×10^{-11} BER in Figs. 15 and 16. For all four channels, better than a 1×10^{-6} BER has been obtained for more than -27.5 dBm received RF power for the back-to-back link and in the complete OSCM link, with a -26.1 dBm received RF power. For all four channels, better than a 1×10^{-6} BER has been obtained for over -11.7 dBm received optical power. As can

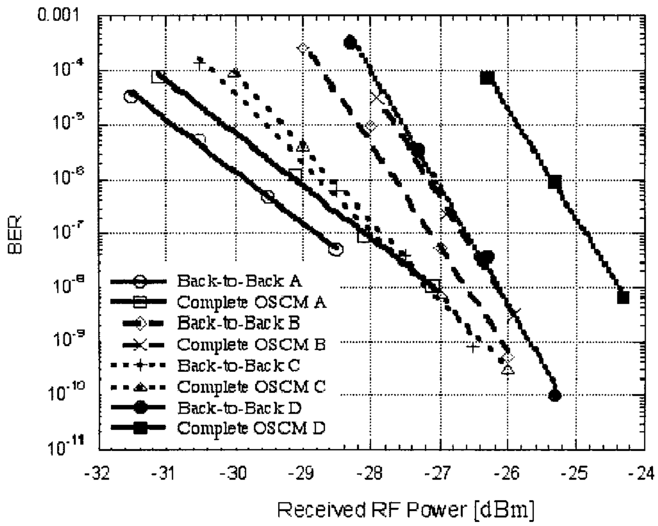

Fig. 15. Measured BER results versus received RF power at point α of Fig. 14 with four active channels.

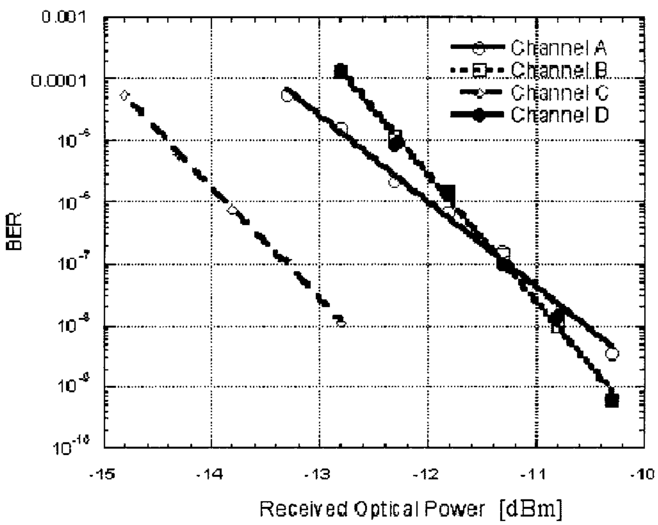

Fig. 16. Measured BER results versus received optical power at point β of Fig. 12 with four active channels.

TABLE V
POWER PENALTY BY OPTICAL LINK

Power Penalty [dB]	Channel A	Channel B	Channel C	Channel D
Four Active Channel	0.6	0.5	0.2	1.4
Single Active Channel	1.0	0.4	0.8	0.8

be seen from the BER test results, the developed single MMIC four-channel transmitter module is well suited for use in a multichannel OSCM communication link. The power penalty due to insertion of an optical link for all four channels are 0.8±0.6 dB, as summarized in Table V and shown in Fig. 15.

The BER measurement results for both back-to-back and the complete OSCM link with only a single active channel for each of the four channels are plotted in Fig. 17. For each of the four channels, better than 1×10^{-6} BER has been obtained for over −34 dBm received RF power in the back-to-back link and above −33.5 dBm received RF power in the complete OSCM link. The power penalty range due to insertion of an optical link for

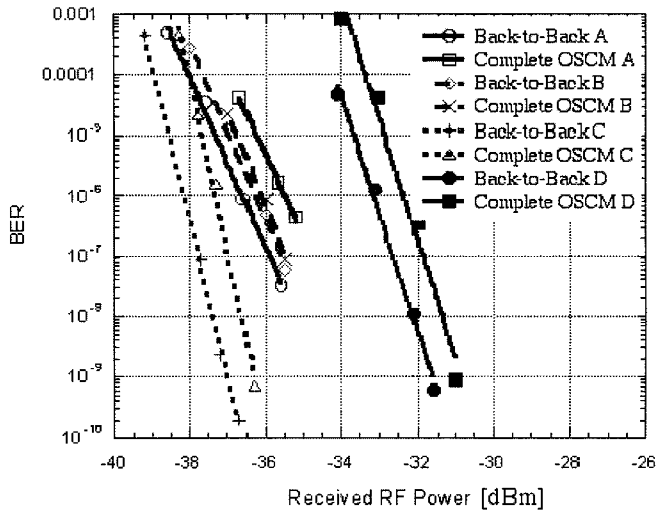

Fig. 17. Measured BER results versus received RF power at point α of Fig. 14 with a single active channel.

TABLE VI
POWER PENALTY OF FOUR CHANNEL OSCM LINK COMPARED TO SINGLE CHANNEL

Power Penalty [dB]	Channel A	Channel B	Channel C	Channel D
Back-to-Back	6.8	8.9	8.0	7.0
Complete OSCM	7.0	8.8	8.2	6.5

the single active-channel case for each of the four channels is 0.7±0.3 dB, as summarized in Table V and shown in Fig. 16. The power penalty for using four active channels instead of a single active channel is 8±1 dB for the back-to-back link and 7.7±1.2 dB for the complete OSCM link, as summarized in Table VI.

VIII. CONCLUSION

A four-channel RF/OSCM communication link single-MMIC transmitter module has been developed and demonstrated in a complete OSCM link. For four active channels, better than 1×10^{-6} BER has been obtained for over −27.5 dBm received RF power for the back-to-back link and over −26.1 dBm received RF power for the complete OSCM link.

The developed module consists of a fully monolithic four-channel transmitter IC and four bandpass filters. A fully monolithic IC, which consists of four VCOs with buffer amplifiers for subcarrier frequency generation and four switch-type FET mixers for OOK subcarrier modulation, has been developed to further reduce cost, size, complexity, and power consumption. Four coupled-line bandpass filters have been designed and fabricated on this module to suppress harmonics and spurious signals and to reduce interchannel crosstalk.

Extensive four-channel OSCM link performance measurements have been performed. By using OOK modulation for the transmitter and direct conversion for the receiver, we have simplified the SCM transceiver architecture and reduced cost. Power penalties have been characterized between the back-to-back and complete OSCM link with all four channels active. Power penalties between the four active-channel case and single active-channel cases for each of the four channels have also been measured. BER test results illustrate that this module is well suited for a four-channel OSCM transmitter.

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Dr. Laskar is a co-organizer and chair for the Advanced Heterostructure Workshop, serves on the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Symposia Technical Program Committee and is a member of the North American Manufacturing Initiative Roadmapping Committee. He was the recipient of the 1995 Army Research Office Young Investigator Award, the 1996 NSF CAREER Award, the 1997 NSF Packaging Research Center Faculty of the Year, the 1998 NSF Packaging Research Center Educator of the Year Award, the 1999 IEEE Rappaport Award (Best IEEE Electron Devices Society journal paper), and was the 2000 corecipient of the IEEE MTT-S International Microwave Symposium (IMS) Best Paper Award.

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In 1981, he was with StorageTek, Louisville, CO, where he was involved in the area of optical data storage. In 1986, he was with Columbia University, where he was involved in the areas of photonic switching systems and ultrafast all-optical networks and signal processing. From 1993 to 1997, he was an Assistant Professor in the School of Electrical and Computer Engineering, Georgia Institute of Technology. He is currently the Associate Director for the Center on Multidisciplinary Optical Switching Technology (MOST) and Associate Professor in the Department of Electrical and Computer Engineering, University of California at Santa Barbara. He heads the Optical Communications and Photonic Networks (OCPN) Research. His current research areas are optical communications, WDM, photonic packet switched and all-optical networks, wavelength conversion in semiconductor devices, OSCM, and multispectral optical information processing. He has authored or co-authored over 40 papers in these and related areas.

Dr. Blumenthal is a member of the Optical Society of America and the IEEE Lasers and Electrooptic Society (LEOS). He is currently an associate editor for the IEEE PHOTONICS TECHNOLOGY LETTERS, an associate editor for the IEEE TRANSACTIONS ON COMMUNICATIONS and was a guest editor for the "Special Issue on Photonic Packet Switching Systems, Technologies and Techniques" of the JOURNAL OF LIGHTWAVE TECHNOLOGY. He was the Program chair for the Optical Society of America (OSA) 1999 Topical Meeting on Photonics in Switching and has served on numerous conference committees, including the program committee for the 1997–1999 Conference on Optical Fiber Communications (OFC). He was the recipient of an NSF Young Investigator (NYI) Award and a Office of Naval Research Young Investigator Program (YIP) Award.