2. G. Calhoun, *Digital Cellular Radio*, (Artech House, Boston, 1988).
3. L. Raddatz, *et al.*, "A Fibre-Optic M-ary Modulation Scheme Using Multiple Light Sources," paper WL36, Optical Fiber Conference, 1997, Dallas, Texas.

CMR5 **2:45 pm**

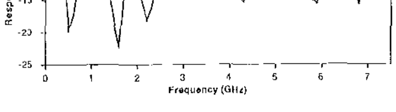
Subcarrier modulation for transmission of 1-Gbit/s channels over 500 m of 62.5-μm multimode fiber

E.J. Tyler, M. Webster, R.V. Penty,
I.H. White, *Centre for Communications Res., Univ. of Bristol, Univ. Walk, Bristol, BS8 1TR, United Kingdom; E-mail: E.J.Tyler@bristol.ac.uk*

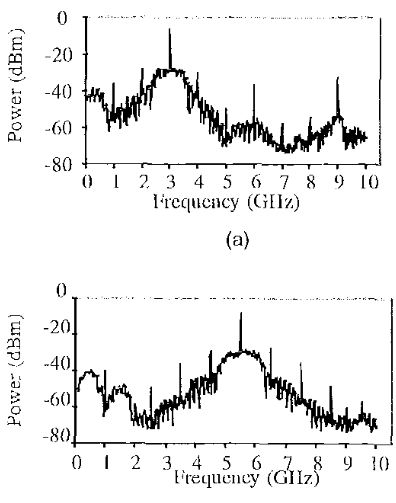
The growing demand for high-speed interconnects for Local Area Network (LAN) applications makes it interesting to study alternative modulation formats to increase the transmission capacity of widely installed 62.5-μm multimode fiber (MMF). For example the available bandwidth for baseband modulation at 850 nm limits Gigabit Ethernet links to distances of 275 m.[1] Subcarrier Multiplexing (SCM) is an attractive technique for increasing the data capacity of existing multimode fiber links. Although SCM has been widely reported for providing broadcast services to cable TV subscribers,[2] SCM transmission over MMF was first achieved by Raddatz *et al.* in 1998.[3] Since then the transmission of 1-Gbit/s BPSK data over 1-km MMF using a single subcarrier at 2.5 GHz has been recorded.[4] In this paper we report the use of two different subcarriers at frequencies up to 5.5 GHz each transmitting 1 Gbit/s over 500 m of MMF.

Using conventional NRZ modulation a data channel is limited in bandwidth by the modal dispersion inherent in multimode fiber. Subcarrier multiplexing presents a way to overcome this limitation by using the regions of fairly flat response at frequencies beyond the fiber's 3-dB frequency. By transmitting several narrowband channels in the passband regions, rather than a single broadband channel, a significant increase in the data transmission capacity of MMF is possible.[5]

The fiber used in the experiments is a 500-m length of 62.5-μm core diameter MMF, which exhibits a near "worst-case" modal bandwidth of 200 MHz.km ($\lambda = 850$ nm). Figure 1 shows the frequency response of the fiber at 850 nm and indicates areas of flat response in the passband at around 3 and 5.5 GHz.



CMR5 Fig. 1. RF frequency response of 500-m multimode fiber showing a 3-dB bandwidth of 400 MHz and regions of relatively flat response located at 3 GHz and 5.5 GHz (wavelength: 850 nm).



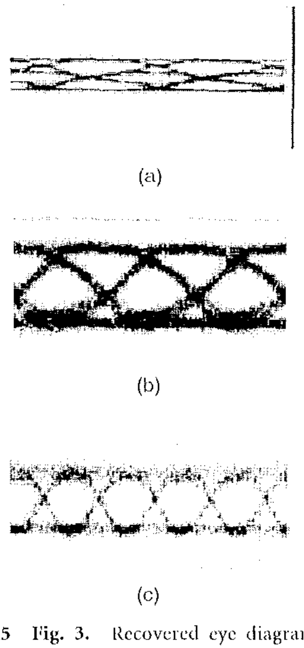
(a)

(b)

CMR5 Fig. 2. RF spectra of transmitted subcarrier signals (a: 3-GHz signal, b: 5.5-GHz signal).

BPSK signals at 3 GHz and 5.5 GHz were generated by modulating a 1-Gbit/s 27-1 PRBS onto the subcarrier in a commercial double balanced mixer. Figure 2 shows the RF spectra of the upconverted signals.

Each signal is fed to a GaAs oxide-confined VCSEL with a threshold of 2 mA and a modulation bandwidth of >7 GHz. After transmission over the fiber the signal is detected using a 7-GHz silicon photodiode and an HP8449B preamplifier. For simplicity the same synthesiser and an identical mixer are used for demodulation. After low pass filtering the data is further amplified to allow bit-error-rate (BER) monitoring.



(a)

(b)

(c)

CMR5 Fig. 3. Recovered eye diagrams of 1-GB/s channels after 500-m fiber (a) Baseband NRZ modulation (500 ps/div, 30 mV/div); (b) 3.0-GHz subcarrier channel (500 ps/div, 50 mV/div); (c) 5.5-GHz subcarrier channel (500 ps/div, 50 mV/div).

The eye diagrams after transmission over 500 m of the "worse-case" fiber are shown in Fig. 3. Using conventional baseband transmission 800 Mbit/s is the maximum data rate obtainable for a BER $<10^{-9}$. However at subcarrier frequencies of 3 GHz and 5.5 GHz open eye diagrams are obtained at 1 Gbit/s and error-free operation is achieved in each case.

SCM transmission represents a significant increase in the link capacity over conventional baseband techniques. By transmitting the two subcarrier channels simultaneously alongside the baseband signal, an aggregate bit rate of 2.8 Gbit/s is possible. This represents an improvement of 250% in transmission performance over the baseband case, which is the highest SCM transmission over MMF yet achieved. Details of this simultaneous transmission will be given at the conference.

1. The Gigabit Ethernet Standard, IEEE standard 802.3z-1998.
2. T.E. Darcie, "Subcarrier multiplexing for Lightwave networks and video distribution systems," J. Sel. Areas Comms. **8,** 1240–1247 (1990).
3. L. Raddatz, *et al.*, "High bandwidth data transmission in multimode fibre links using subcarrier multiplexing with VCSELs," Electron. Lett. **34,** 686–688 (1998).
4. T.K. Woodward, *et al.*, "1 Gb/s BPSK transmission at 850 nm over 1 km of 62.5 μm-core MMF using a single 2.5 GHz subcarrier," IEEE Photon. Technol. Lett. **11,** 382–384 (1999).
5. L. Raddatz, *et al.*, "High bandwidth multimode fibre links using subcarrier multiplexing in vertical cavity surface emitting lasers," in *Optical Fiber Communication Conference*, OSA Technical Digest, 358–359 (1998).

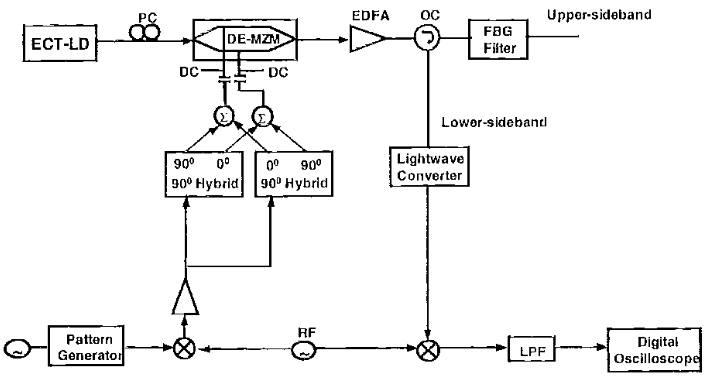
CMR6 **2:45 pm**

A "tandem" single sideband fiber-optic system using a dual-electrode Mach–Zehnder modulator

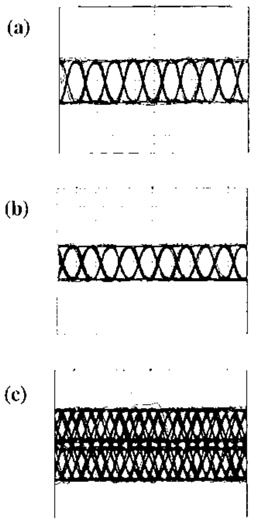
A. Narasimha, X.J. Meng, M.C. Wu,
E. Yablonovitch, *Electrical Engineering Department, Univ. of California, Los Angeles, 64-144 Engineering IV, 420 Westwood Plaza, Los Angeles, California 90095, USA; E-mail: adit@ee.ucla.edu*

Optical single sideband (SSB) modulation has received great interest as a way to reduce the dispersion penalty of analog fiber-optic systems.[1,2] In this paper, we propose and demonstrate a "tandem" single sideband fiber-optic link, which uses a dual-electrode Mach–Zehnder (M–Z) modulator to place different information in each of the two sidebands, thus doubling the bandwidth efficiency.

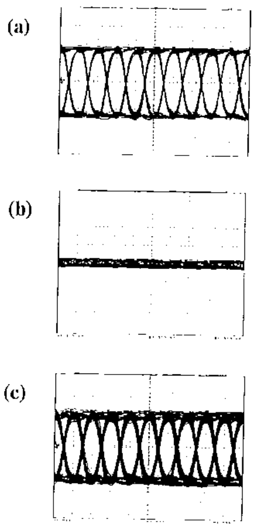
Figure 1 shows the experimental setup. The light source is an external cavity tunable laser diode (ECT-LD). The light from the ECT-LD is coupled into a dual-electrode Mach–Zehnder modulator (DE-MZM) through a polarization controller. An externally triggered pattern generator with 2^{23}-1 pseudorandom bit sequences (PRBS) provides the baseband signal at a rate of



CMR6 **Fig. 1.** Experimental setup.



CMR6 **Fig. 2.** Eye diagrams with laser frequency at center of fiber grating when (a) only lower sideband is transmitted (b) only upper sideband is transmitted (c) both sidebands are transmitted.



CMR6 **Fig. 3.** Eye diagrams with laser wavelength up-shifted by 10 GHz when (a) only lower sideband is transmitted (b) only upper sideband is transmitted (c) both sidebands are transmitted.

500 Mbps. The data is modulated by BPSK onto a subcarrier at a frequency f_c = 12 GHz. The signal is split into two and fed to two 90° hybrids through two different path lengths. The 0° output from each hybrid is summed with the 90° output of the other hybrid and the two resultant signals are used to drive the DE-MZM through bias Ts. The DE-MZM is biased at quadrature. The two BPSK signals are thus carried on different sidebands of the optical carrier. The power before the RF power divider is 20 dBm. An erbium-doped-fiber-amplifier (EDFA) boosts the output optical power. At the receiver, both the upper and lower sidebands are separated by a reflective fiber grating (FWHM = 20 GHz) through an optical circulator (OC). The signal is detected by a Lightwave converter (HP 11982A). The output is connected to a low pass filter (LPF) followed by a digital oscilloscope (HP 54542C) to observe eye diagrams.

The experiment is performed at two wavelengths of the laser source. In the first case, the laser wavelength is chosen such that it lies at the center frequency of the fiber grating. This ensures that both sidebands are almost equally accepted. The experiment is then repeated with the laser wavelength up-shifted by 10 GHz. This ensures that the upper sideband is almost completely rejected. In each of the above cases the sidebands are first transmitted individually and then together through appropriate input to the DE-MZM.

In Fig. 2 the light source wavelength was at the center of the fiber grating. We can see from the eye diagrams that both sidebands are accepted nearly equally. The fact that the eye diagram deteriorates when we transmit both sidebands suggests that we are transmitting different signals in each of the sidebands.

In Fig. 3 the source wavelength is up-shifted by 10 GHz. As can be seen, the upper sideband is almost completely rejected resulting in an excellent eye diagram even when both the side bands are transmitted.

The above results suggest that the "tandem" transmission was successful and that it is possible to transmit different information in both the side bands.

In conclusion, we have successfully demonstrated the "tandem" single sideband technique and shown that it is possible to double the bandwidth efficiency of a link by transmitting different information in each of the two sidebands.

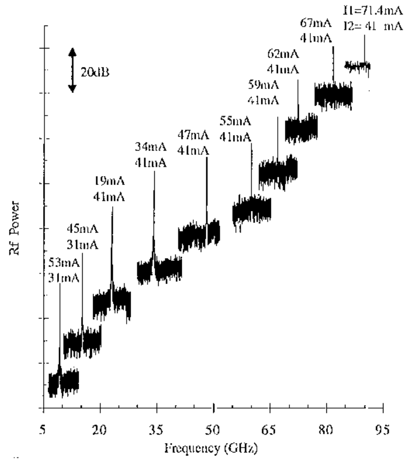
1. G.T. Smith, D. Novak, Z. Ahmed, "Technique for Optical SSB Generation to Overcome Dispersion Penalties in Fiber-Radio Systems," Electronics Lett. **33,** 74 (1997).
2. M.Y. Frankel, R.D. Esman, "Optical Single-Sideband Suppressed-Carrier Modulator for Wide-Band Signal Processing," J. Lightwave Tech. **16,** 859 (1998).

CMR7 **3:00 pm**

Optical generation and self sub-harmonic injection locking of tunable 10–100 GHz microwave/millimeter signals

M. Al-Mumin, X. Wang, W. Mao, G. Li, Stephen A. Pappert,* *CREOL, Univ. of Central Florida, 4000 Central Florida Blvd., Orlando, Florida 32816-2700, USA; E-mail: li@creol.ucf.edu*

Optical techniques for generation of RF signals are becoming increasingly important in applications requiring very high frequencies and narrow linewidth microwave/millimeter signals such as fiber-radio systems for broadband wireless. Two-section distributed feedback (DFB) lasers exhibiting high frequency self-pulsation signals up to 80 GHz has been reported.[1,2] The frequency of microwave/millimeter signals from the two-section DFB lasers is controlled via the bias current of the two sections. In this paper we report on a continuous RF tuning from 10 to a 100 GHz measured electronically by optical downconversion. These microwave/millimeter wave signals have a free running linewidth in the order of a few MHz, unacceptable for many applications. We achieved stabilization and linewidth-reduction by using self sub-harmonic locking technique, different from ordinary sub-harmonic injection locking. In ordinary sub-harmonic locking, frequency multiplication of the sub-harmonic is achieved by over modulating a master laser with a high-power sub-harmonic signal. In self sub-harmonic locking reported here, frequency multiplication of sub-harmonic is achieved via intra-cavity nonlinearity. The self sub-harmonically lock sig-



CMR7 **Fig. 1.** RF spectrum as a function of current bias.