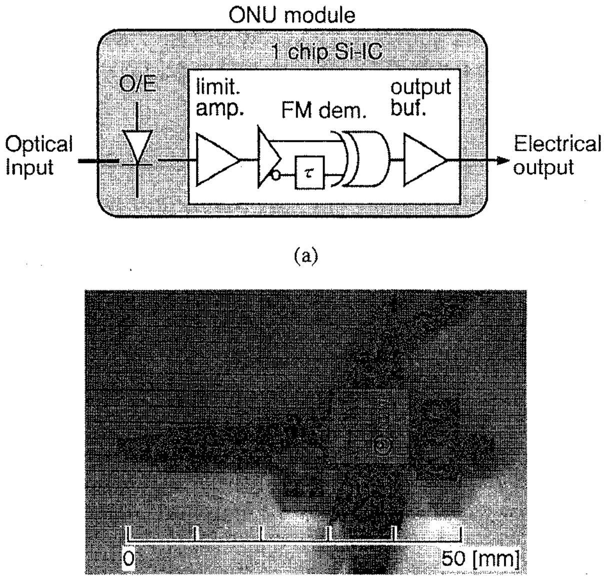


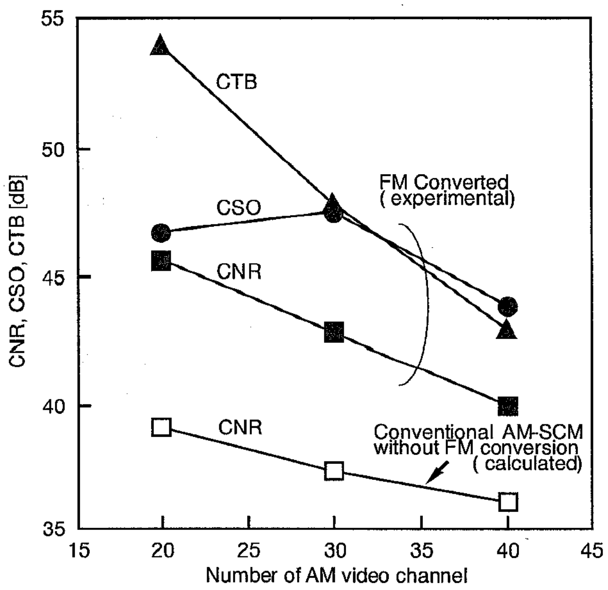
(a)

(b)

ThT4 Fig. 2. Small ONU module for FM converted multichannel video signal transmission systems: (a) schematic block diagram; (b) photograph. Width 27 mm, height 10 mm, depth 18 mm.

existing TV tuners. Because the wiring for high frequency signals is reduced in the proposed module, the cost can be reduced.

Figure 3 shows the carrier-to-noise ratio (CNR), composite second-order (CSO) distortion, and composite triple beat (CTB) versus number of AM video channels. Received optical power was adjusted to -15 dBm, and pre-distortion circuits were used to compensate for CSO and CTB. Compare with conventional AM-SCM systems without FM conversion,[4] CNR is improved by >4.8 dB. As the number of video channels increases, the CNR are degraded because the frequency deviation must be reduced. Therefore, the linear range of the demodulator should exceed 5.5 GHz to improve the CNR. On the other hand, the degradation of CSO and CTB is due to the nonlinearity of the demodulator caused by group delay of the limiting amplifier and so on.



ThT4 Fig. 3. CNR, CSO, CTB vs. number of AM video channel. Received optical power is -15 dBm. Measured frequency is at worst case channel. Pre-distortion circuits are used for CSO and CTB compensation. Frequency deviation are 173, 148, 114 MHz0-p/ch for 20, 30, 40 AM video channel transmission, respectively. The linewidth of FM laser and local laser are 150 and 17.9 kHz, respectively.

In conclusion, we have proposed a small ONU module for FM converted multichannel video signal transmission systems, and demonstrated multichannel video signal transmission.

*NTT Optical Electronics Laboratories

**NTT Affiliated Business Headquarters

1. K. Kikushima, K. Suto, H. Yoshinaga, H. Nakamoto, C. Kishimoto, M. Kawabe, K. Kumozaki, N. Shibata, presented at IOOC'95, 1995, paper PD 2-7.
2. N. Sakurai, C. Kishimoto, K. Kikushima, K. Kumozaki, N. Shibata, T. Sugie, presented at OECC'97, 1997, paper 10A1-3.
3. K. Kikushima, C. Kishimoto, S. Ikeda, N. Sakurai, K. Kumozaki, N. Shibata, T. Sugie, presented at ECOC'97, session WE2B.
4. R.C. Menendez, C.N. Lo, S.S. Wagner, W.I. Way, Proc. Natl. Commun. **43(2)**, 737–742 (1989).

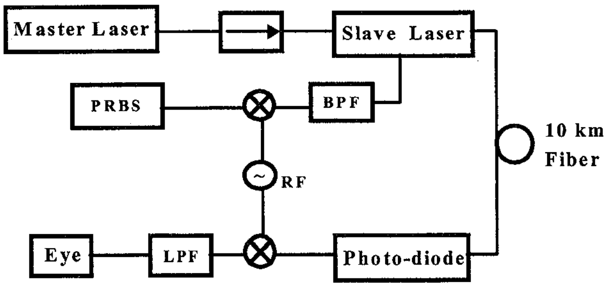
ThT5 5:00pm

Modeling of an analog fiber-optic link with an injection-locked semiconductor laser

Xue Jun Meng, Ming C. Wu, *UCLA, Electrical Engineering Department, 405 Hilgard Ave., Los Angeles, California 90095-1594*

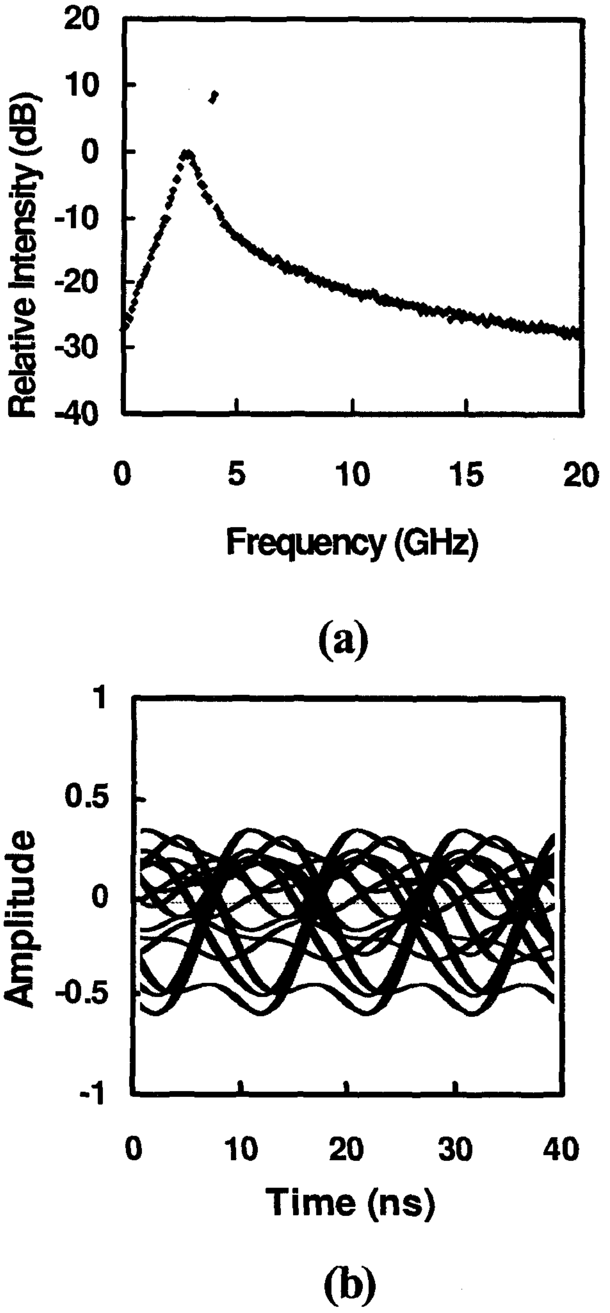
Sub-carrier-modulated (SCM) fiber-optic systems have applications in cable television distribution,[1,2] and phased array antenna systems. The transmission capacity of the SCM system employing direct laser modulation is generally limited by the bandwidth of the semiconductor laser. Recently, several groups have proposed the use of strong injection-locking technique[3,4] to enhance the modulation bandwidth. In this report, we present, to our knowledge, the first theoretical investigation of an analog optical fiber link using a directly-modulated semiconductor laser under strong injection-locking. The analysis is based on rate equations, which include phase and amplitude noises in both master and slave lasers.

Figure 1 shows the schematic diagram of the system under consideration. The signal of the master laser is injected into the slave laser, which is directly modulated by a microwave subcarrier with a BPSK data signal with 4% modulation index. The data stream is a NRZ, 2^{17}-1 PRBS at 100 Mbit/s. The optical signal is transmitted over a 10-km-long standard single-mode fiber at 1550 nm and directly detected at the receiver. A



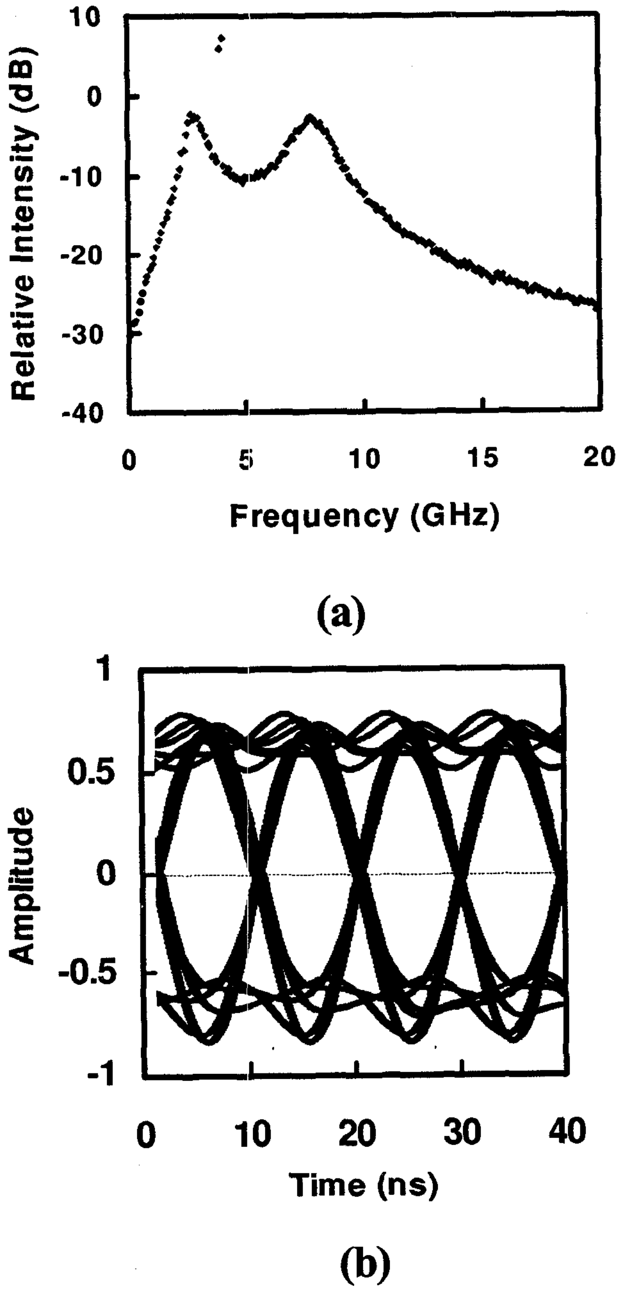
ThT5 Fig. 1. Schematic diagram of an analog fiber-optic link with injection-locked semiconductor laser source.

cosine roll-off low-pass filter with the roll-off factor of 0.5 is employed to shape pulse waveforms. The parameters of both the master and slave lasers are summarized below: The resonance frequency, the linewidth, and the linewidth enhancement factor under free running condition are 2.95 GHz, 13.5 MHz and 4, respectively. The carrier and photon lifetimes of the laser are 0.69 ns and 4.2 ps, respectively. Figure 2(a) shows the power spectrums of the free-running slave laser modulated at RF carrier frequency = 4 GHz. Figure 2(b) shows the corresponding eye diagram. As expected, when the RF carrier frequency exceeds the resonance frequency of the laser, a chaotic eye pattern is observed.



ThT5 Fig. 2. (a) Power spectrum and (b) corresponding eye diagram of the free-running slave laser under SCM modulation with RF = 4 GHz, 4% modulation index and 100 Mbit/s PRBS.

We examine the slave laser with same modulation signal as above under injection-locking. The injection-locking range considered here is similar to those reported.[4] Figure 3(a) shows the power spectrum of the slave laser under injection-locking for RF carrier frequency of 4 GHz. To achieve stable injection-locking, the frequency detuning of the injection signal with respect to the free-running frequency of the slave laser is −4 GHz and the injection power ratio are chosen to be 0.2. In Fig. 3(a), a new resonance peak appears at 8.07 GHz, which is higher than the original one by 5.12 GHz. It is important to note that, because we include phase and amplitude noises in the master laser, the output power spectrum still retains the original resonance peak from the master laser, although its amplitude is reduced. This is different from previous studies[3,4] in which



ThT5 Fig. 3. (a) Power spectrum and (b) corresponding eye diagram of the injection-locked slave laser under SCM modulation with RF = 4 GHz, 4% modulation index and 100 Mbit/s PRBS.

a perfect master laser is considered. This leads to an increase in modulation bandwidth even when the master laser has the same noise as the slave laser. Significant improvement in the link performance has been achieved by employing strong injection-locking, as illustrated by the eye diagrams in Fig. 3(b). In summary, strong injection-locking has been shown to be a very effective and practical approach to significantly improve performance of sub-carrier-modulated fiber-optic systems at frequencies beyond the bandwidth of directly-modulated semiconductor lasers.

1. W.I. Way, IEEE J. Lightwave Technol. **7**, 346 (1989).
2. G.R. Joyce and R. Olshansky, IEEE Photon. Technol. Lett. **4**, 665 (1992).
3. L. Li, IEEE J. Quantum Electron. **30**, 1701 (1994).
4. J.M. Liu, H.F. Chen, X.J. Meng, T. Simpson, IEEE Photon. Technol. Lett. **9**, 1325 (1997).

ThT6 5:15pm

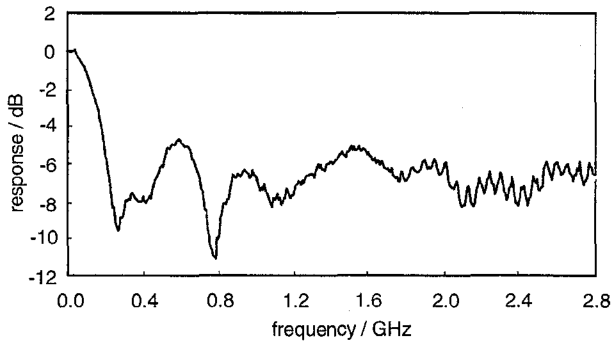
High bandwidth multimode fiber links using subcarrier multiplexing in vertical-cavity surface-emitting lasers

L. Raddatz, D. Hardacre, I.H. White, R.V. Penty, D. G. Cunningham,* M.R.T. Tan,** S.-Y. Wang,** *Centre for Communications Research, University of Bristol, Bristol BS8 1TR, United Kingdom; E-mail lutz.raddatz@bristol.ac.uk*

There is currently much interest in low-cost high-speed and short-haul links for local area networks and computer interconnect applications, with standards bodies such as those setting the Gigabit Ethernet standard now considering transmission rates in excess of 1 Gbit/s.

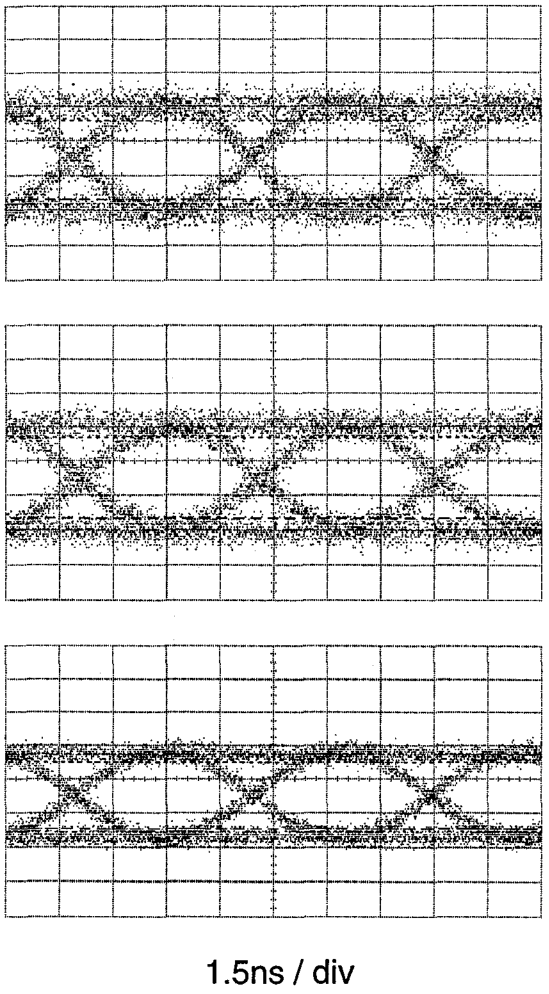
Because of cost, particular emphasis has been placed on the use of multimode fiber (MMF) links using vertical-cavity surface-emitting lasers (VCSELs). With increasing data rates however the achievable link lengths become limited due to the modal bandwidth of the MMF. Efforts to overcome this limitation have included the use of wavelength-division multiplexing,[1] multilevel modulation[2] and restricted mode launches.[3] In this paper, however we believe we describe for the first time how subcarrier multiplexing (SCM) techniques can be used to allow link transmission significantly in excess of the specified fiber bandwidth. The technique is robust and has been assessed using a representative range of fibres. A series of 200-Mbit/s channels with carrier frequencies of up to more than twenty times the 3-dB fiber bandwidth have been successfully used, the maximum being limited by the electronics currently available to us.

The studies of subcarrier multiplexing have used 850-nm GaAs VCSELs as sources, transmitting over 62.5 μm core diameter MMF. Figure 1 shows the measured frequency response of a 1000-m long fiber, typical of its type. At low frequencies the response falls off with an approximately Gaussian shape, allowing the fiber to have a 3-dB bandwidth of 180 MHz at this wavelength. At higher frequencies however, the response is relatively flat with a loss level of approximately 7 dB relative to the low frequency regime. It should be noted that the ripples observed at frequencies >2 GHz are caused by reflections and are not effects of the fiber response. The flatness of this response can be understood by noting that if chromatic dispersion effects are neglected, the impulse response of the complete fiber can be considered as a sum of impulses with different delays corresponding to each mode. As a result at high frequencies, the frequency response of the fiber does not fall off.



ThT6 Fig. 1. Frequency response of 1000 m of 62.5-μm core MMF using an 850-nm VCSEL.

To assess the transmission of the fiber at these higher frequencies, digitally modulated channels are placed on high frequency carrier signals and then used to modulate a VCSEL. After transmission through the MMF and detection, the baseband signal is recovered and displayed on an oscilloscope. A selection of the eye diagrams obtained using 200-Mbit/s streams at various carrier frequencies are shown in Fig. 2. Good quality eye diagrams are obtained for carrier frequencies up to 3.8 GHz,



ThT6 Fig. 2. Recovered eye diagrams for a 1-km-long MMF SCM link at different carrier frequencies (top: 1.4 GHz, middle 2.6 GHz, bottom: 3.8 GHz). The channel bandwidth is 200 Mbit/s in each case.