High-Fidelity Lightwave Transmission of Multiple AM-VSB NTSC Signals

JAN LIPSON, L. CHAINULU UPADHYAYULA, SENIOR MEMBER, IEEE, SUN-YUAN HUANG, MEMBER, IEEE, CHARLES B. ROXLO, E. J. FLYNN, PAUL M. NITZSCHE, CARL J. McGRATH, GERALD L. FENDERSON, AND MARK S. SCHAEFER

(Invited Paper)

Abstract —In this paper we report on progress towards developing AM lightwave links for the transmission of multiple TV signals. While the signal quality objectives and transmission distances are appropriate for the CATV trunking application, the technology is ultimately expected to have applicability to the distribution of video signals in the subscriber loop. Highly linear 1.3 μm DFB lasers, designed expressly for analog requirements, were used to transmit 42 continuous wave carriers according to the standard U.S. CATV frequency plan. For our best lasers, when evaluated over 12 km of fiber, carrier to noise, composite second-order distortion, and composite triple beat were > 52 dB, > 70 dBc, and > 70 dBc, respectively. The relationship between measurements with CW carriers and actual video signals is discussed. System design rules are offered. Properties that lead to superior analog performance are discussed. Data from > 700 links indicate that composite third-order distortion generally scales with product count but that composite second-order distortion has a significant frequency-dependent component.

I. Introduction

As LIGHTWAVE technology has begun to penetrate closer to the subscriber, there has been an intensive interest in the cost-effective transmission of large numbers of TV signals. Centrally switched wide-band distribution systems [1]–[5] possess many attractive features but have initially proven too expensive for widespread deployment. Broadcast architectures have been proposed and/or demonstrated using digital [6], subcarrier FSK [2], [3], [7], PSK [8], FM [9], [10], and AM [11] signal formats. Each option may be judged according to the following criteria:

1) cost
2) compatibility with existing equipment
3) signal quality
4) possibility of gradual introduction (entry strategy)
5) flexibility (ease of upgrade).

Digital systems typically suffer high costs associated with the conversion of the signal to the required AM format at the receiver. While such costs can be ameliorated to some extent by the use of time division multiplexing, inflexibility in the provision of additional channels may arise. Subcarrier FM and FSK systems are, in some embodiments, likewise subject to the high costs of converting each individual channel to AM. Again, conversion costs may be reduced if the signal is transported without demodulation directly to the subscriber. Once on the subscriber's premises, it is generally necessary to recover only one AM channel per television receiver. While there are no obvious technical deficiencies associated with such a scheme, high conversion costs are avoided only if the distribution part of the system is deployed simultaneously with the trunking or feeder plant. A more graceful strategy for introduction of lightwave technology into the loop is to begin the deployment in those parts of the system where the cost is shared by numerous subscribers. Introduction into the most cost-intensive parts of the plant occurs when sufficient production experience has enabled the supplier to achieve satisfactory costs.

The principal disadvantage of AM transmission has been the fragility of the signal with respect to noise and distortion. Until very recently, nonlinearities in the laser sources prevented the transmission of a sufficient number of channels with adequate signal quality. A number of workers have endeavored to evade this restriction through the use of linearizing techniques [12]–[15]; however the additional complication and cost may be disadvantageous if a suitably linear laser is available. In this paper we describe a system in which 40–80 channels of AM-VSB NTSC signals can be transmitted over 12 km of fiber, with negligible impairment in the perceived quality of the signal. The modulation index is adjusted so that the carrier to noise ratio (C/N) always exceeds 50 dB. The transmitter makes use of a highly linear 1.3 μm DFB laser in conjunction with suitable ancillary circuitry. Numerous systems of this type have been deployed in commercial CATV trunking applications, and they are gaining widespread acceptance in the industry. The organization of this paper is as follows. In Section II the architecture of the link is discussed. Included is a discussion of optical reflections as

Manuscript received August 18, 1989; revised October 28, 1989.
J. Lipson, L. C. Upadhyayula, and S.-Y. Huang are with AT&T Bell Laboratories, Route 222, Breinigsville, PA 18031.
C. B. Roxlo, E. J. Flynn, and P. M. Nitzsche are with AT&T Bell Laboratories, 600 Mountain Ave., Murray Hill, NJ 07974.
C. J. McGrath, G. L. Fenderson, and M. S. Schaefer are with AT&T Bell Laboratories, 1600 Osgood Street, North Andover, MA 01845.
IEEE Log Number 8934045.

0018-9480/90/0500-0483$01.00

well as a comparison of test results using CW carriers and live TV signals. Section III contains a description of the devices. Consideration is also given to laser packages and optical isolators. Finally, both the current status and the potential evolution of analog technology are summarized in Section IV.

II. CATV System Considerations

A. Link Architecture

A simple model of a fiber-optic CATV trunk system is shown in Fig. 1. The head-end electronics are modeled as N (N being the number of channels) video modulators, each converting a baseband video and audio signal to a AM-VSB signal at a frequency f_n. The individual outputs are passively combined in several stages to form the composite spectrum. A typical head-end spectrum begins at 55 MHz (channel 2) and may progress to frequencies as high as 550 MHz for an 80 channel system.

Several CATV frequency plans are in use in the United States, all having the same basic spectral structure depicted in Fig. 2. Unmodulated carriers, as generated by the most commonly used test instrumentation, are shown representing the carrier frequency of each CATV channel. Carriers are spaced at 6 MHz increments with predetermined gaps for FM broadcast and certain communication channels.

As a broad-band transmission vehicle, AM links for CATV applications are characterized by the following figures of merit [16]:

- C/N — Carrier to noise ratio: the ratio of the peak carrier power for a given channel to the noise floor near the carrier, assuming a noise bandwidth of 4 MHz.
- CTB — Composite triple beat: the ratio of the peak carrier to the peak power in the composite third-order intermodulation tone, which, for the frequency plan used in these studies, occurs at the carrier frequency.
- CSO — Composite second order: the ratio of the peak carrier to the peak power in the composite second-order intermodulation tone. For standard and IRC (incrementally related carriers) frequency plans, the CSO appears at the carrier frequency ± 1.25 MHz. For the HRC (harmonically related carriers) frequency plan, the CSO beats appear under the carriers, as with CTB.

We will examine C/N and intermodulation performance separately, because the noise performance of most components is well understood and may be accurately modeled, whereas intermodulation performance must be characterized on each individual transmitter/receiver.

B. C/N—Noise Sources in a Fiber-Optic AM Link

A simplified model [17] of the broad-band link is shown in Fig. 3, for noise performance considerations. There are three dominant sources of noise, all of which are modeled as current sources.

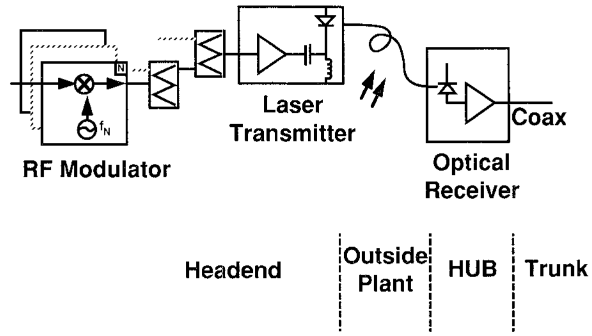


Fig. 1. Schematic for a CATV system utilizing an AM fiber trunk.

1) Front-End Noise: For this analysis, the noise power from the preamplifier is converted to equivalent input current and expressed in pA/(Hz)$^{1/2}$. In general, the equivalent input noise current is not flat across the band and will vary with temperature and load conditions. The noise performance of the preamplifier used in these broad-band applications is typically in the range 12–16 pA/(Hz)$^{1/2}$.

2) Shot Noise: The quantum or shot noise, I_s, formed in an ideal square law detector is given by

$$\bar{I}_s^2 = 2eI_p\frac{A^2}{H_z} \tag{1}$$

where e is the electronic charge and I_p is the detected current. Over the frequency range of interest, the shot noise is essentially flat.

3) Relative Intensity Noise: The final dominant noise source in the AM system is laser intensity noise as characterized by RIN in dB/Hz [18]. The apparent intensity noise at the receiver consists of noise intrinsic to the laser (quantum effects in electron to photon conversion, mode partitioning, etc.) and extrinsic effects which may be caused by reflections and dispersion. Reflection effects are discussed in subsection II-E. For AM trunking applications an RIN of < -150 dB/Hz is normally required.

C. Intermodulation Noise—CTB and CSO

The theory and mathematics of intermodulation noise are well developed [19], having become particularly important in CATV applications [20] when channel loads on coaxial cable exceed the original 13 off-air channels.

The linearity of lasers is discussed extensively in subsection III-A. The applied modulation current to the laser is given by

$$I(t) = I_0 + (I_0 - I_{\text{th}})\sum_{i=1}^{N} m_i\cos(2\pi f_i t + \phi_i) \tag{2}$$

where I_0 is the dc bias current, I_{th} is the threshold current of the laser, m_i is the modulation index for the ith carrier, and ϕ_i is the phase of the ith carrier. The light output,

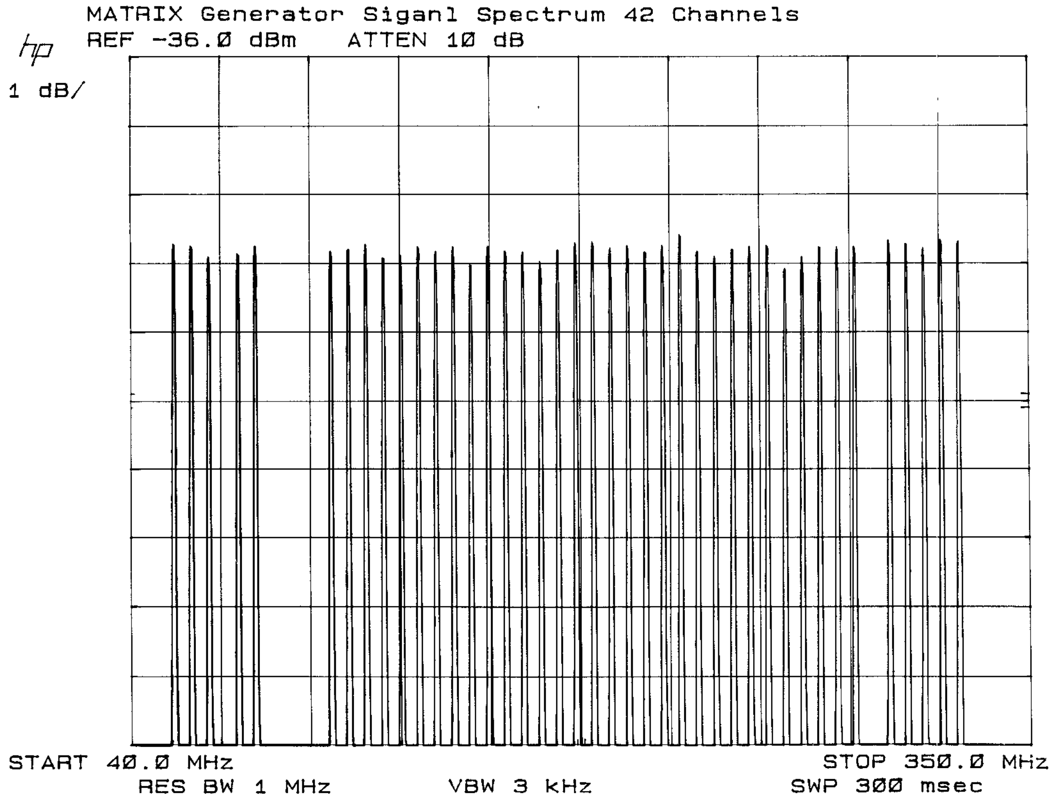


Fig. 2. Frequency spectrum produced by a 42 channel multicarrier test source used in CATV measurements.

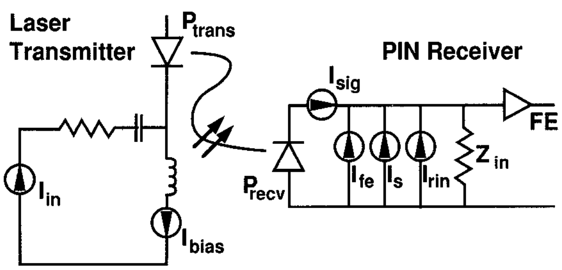


Fig. 3. Equivalent circuits for transmitters and receivers.

$L(t)$, in response to the modulation is given by

$$L(t) = L_0 + \sum_{i=1}^{N} \frac{\left(\dfrac{d^n L}{dI^n}\right)}{n!} [I(t) - I_0]^n \qquad (3)$$

where L_0 is the power at the dc bias current. If terms beyond $i = 3$ are negligible, we will expect power to appear at $f_i \pm f_j$, and $f_i \pm f_j \pm f_k$. In addition, other elements in the system may have nonlinear transfer characteristics such as the laser driver, the p-i-n detector, and receiver amplifiers. We find, however, that typical links are dominated by laser nonlinearity.

Each composite second- or third-order beat is made up of tones of equal amplitude assuming that the generating spectrum is flat. If the nonlinearity is frequency dependent [21], [22], the contributions from each tone can still be equal, provided that the amplitude of the tone depends only on the resultant frequency and not on the individual frequencies of which it is composed. If we assume that the tones are uncorrelated in phase and that the nonlinearity is frequency independent, then the expected channel to channel relative differences in intermodulation performance will follow a 10 log(N_0) scaling, where N_0 is the number of second- or third-order products. In Figs. 4 and 5, we show a plot of the predicted relative second-order and third-order intermodulation performance for 42 CATV channels. It can be seen that CSO performance is expected to be most critical at both the high and low ends of the band, where product counts are highest, whereas CTB is most signifi-

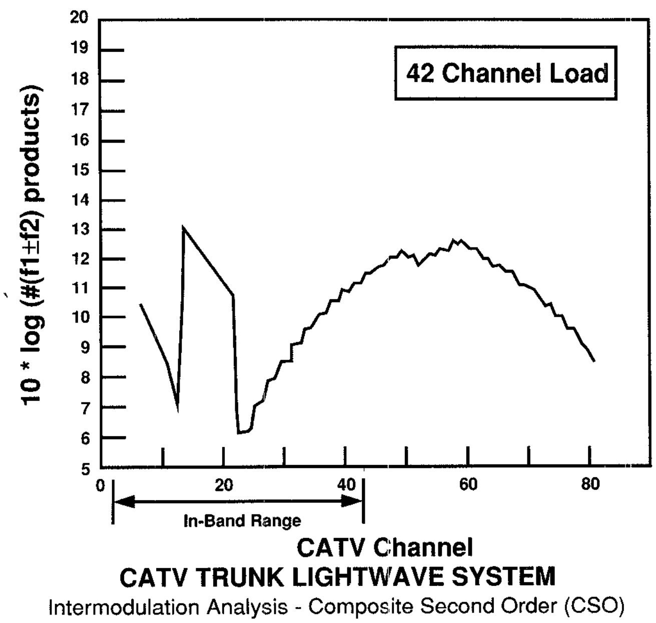


Fig. 4. 10 log (number of second-order intermodulation products) for a 42 channel system.

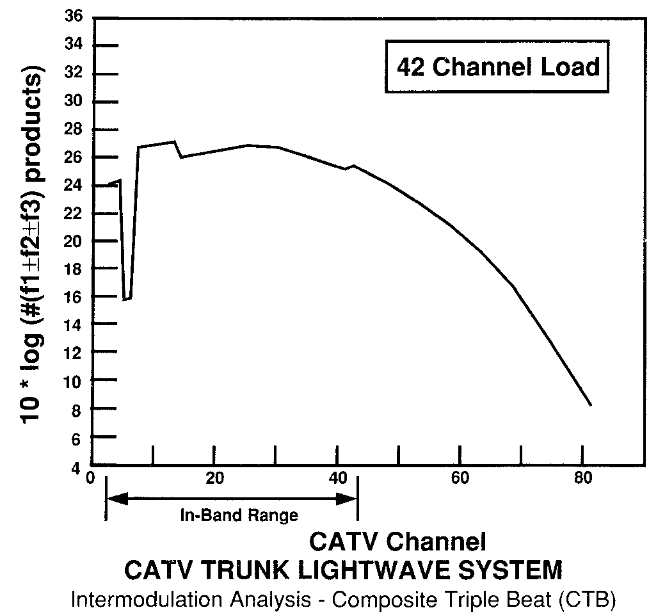


Fig. 5. 10 log (number of third-order intermodulation products) for a 42 channel system.

cant in the middle of the band, where third-order product counts are highest.

D. System Performance

A typical hardware implementation for CATV applications includes a laser transmitter with associated power supplies, bias circuits, thermoelectric cooler control circuits, and RF drive stages. The optical detector (p-i-n), preamplifier, postamplifier, and power supply are mounted in a rugged outside cable plant housing suitable for general deployment in CATV networks.

A diagram of a typical evaluation arrangement for the link is shown in Fig. 6. The band-pass filter, amplifiers, and variable attenuators are used to optimize the performance of the spectrum analyzer with respect to linearity and noise contribution (i.e., dynamic range). Using NCTA-recommended procedures, typical results shown in Fig. 7 were achieved. Data from a typical 42 channel link with out-of-plant losses of 5 dB (12 km fiber) are analyzed in Table I, where all the noise contributions are reduced to an equivalent input noise current. Performance superior to the typical values summarized in Table I can be obtained with our best lasers. For the best links, we have achieved $C/N > 52$ dB, $CSO > 70$ dBc, and $CTB > 70$ dBc. When the matrix generator in Fig. 6 is replaced by an actual CATV head end with live video modulation, the carrier amplitude is reduced by an average of 6 dB. This results in an improvement in measured CTB of approximately 12 dB and an improvement in CSO of approximately 6–10 dB. Because these levels of performance are well below the level at which an impairment is typically perceived, the modulation index of the device is usually increased to provide a more optimum trade-off of C/N and intermodulation distortion.

E. Enhanced Noise from Optical Reflections

The adverse effects of optical feedback on semiconductor lasers has been studied intensively with respect to degradations in the optical spectrum [23] and noise performance [24], [25]. Reference [25] is particularly useful in that the degradation of RIN as a function of the polarization of the optical feedback is also explored. Potential sources of reflections include the laser package optics, the optical isolator, connectors, splices, the receiver, and Rayleigh backscattering from the fiber itself [26]. The effect of optical feedback on laser relative intensity noise does not become negligible until a total return loss of > 50 dB is obtained when typical distances to the source are of the order of several meters [25]. In this context, return loss is referenced to the power emerging from the laser facet and includes coupling and other losses. In addition, the noise spectrum acquires periodic peaks at frequencies corresponding to an inverse round-trip time between the laser and the source of the optical feedback. This phenomenon is shown in Fig. 8(a), where the periodicity of the peaks in the noise spectrum corresponds to the location of an optical isolator having a return loss of approximately 60 dB. Fortunately, when modulation is applied to the laser the coherence is substantially suppressed and much smaller effects are observed in the noise spectrum (Fig. 8(b)).

Nominally, the optical isolators employed in this system have isolation of approximately 30 dB (see subsection III-C); consequently the sum of all other return losses must exceed 20 dB. To ensure this, we employ rotary mechanical splices in the system [27] with typical return losses of 40 dB. Fiber return loss is itself in the regime of 32 dB, and is essentially irreducible. This distributed reflection has been shown to enhance laser intensity noise [28]. Because of the presence of the optical isolator, we have been unable to observe a measurable distortion penalty associated with the inclusion of fiber in the system.

A second degradation associated with reflections is the interferometric conversion of laser phase noise to intensity noise [29]. In the limit where the distance between reflectors is much larger than the coherence length of the laser, it can be shown that the carrier to noise ratio is limited by the following inequality [30]:

$$\frac{C}{N} < \frac{\sqrt{2\pi}}{8} \frac{m^2}{R^2} \frac{B_1}{B_s} \tag{4}$$

where R is the geometric mean of the reflectivities, B_1 is the spectral width of the laser due to chirping (HWHM), B_s is the noise bandwidth of an individual TV channel, and m is the modulation index per channel. Taking typical values for B_1 (4 GHz), B_s (4 MHz), and m (0.04), we find that $C/N < 55$ dB if $R > -29$ dB.

A final degradation associated with the presence of optical cavities is the conversion of the FM modulation of the laser to amplitude distortion [31]. In the regime where the chirp of the laser under modulation is of the order of the free spectral range of the interferometer, large contributions (> 20 dB) to both the second- and third-order

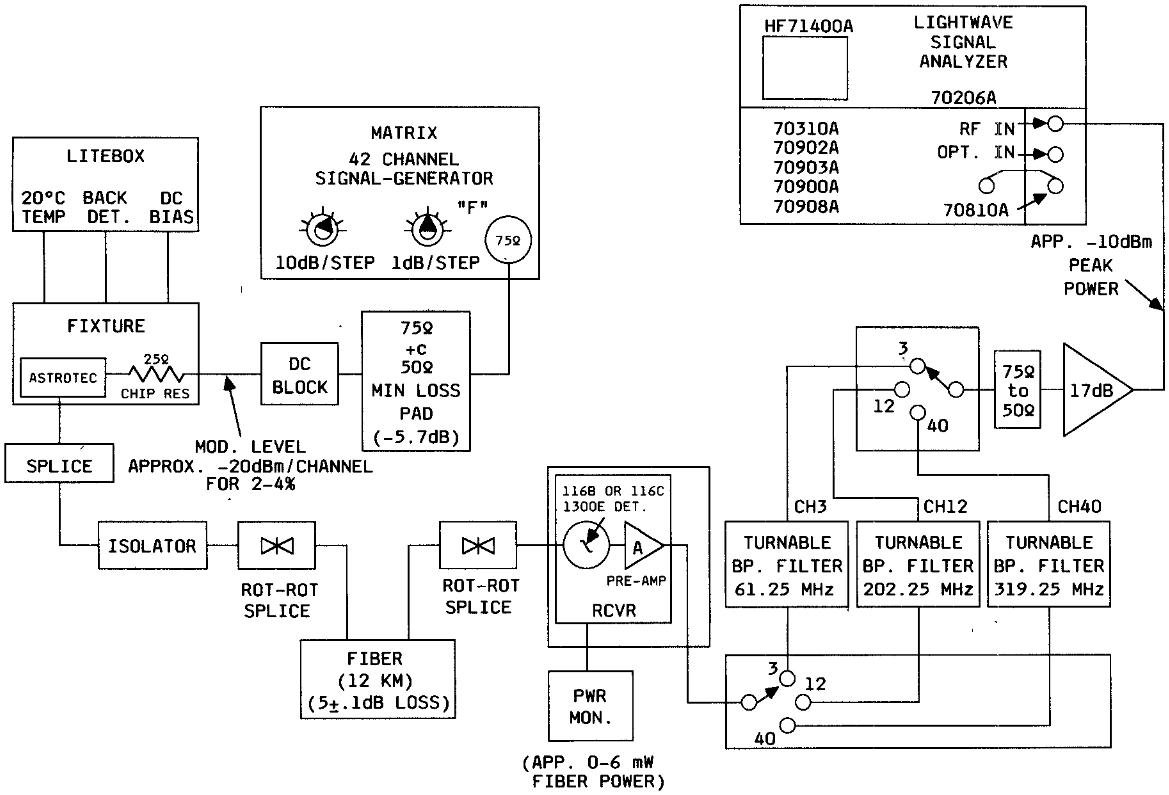


Fig. 6. Schematic of measurement apparatus.

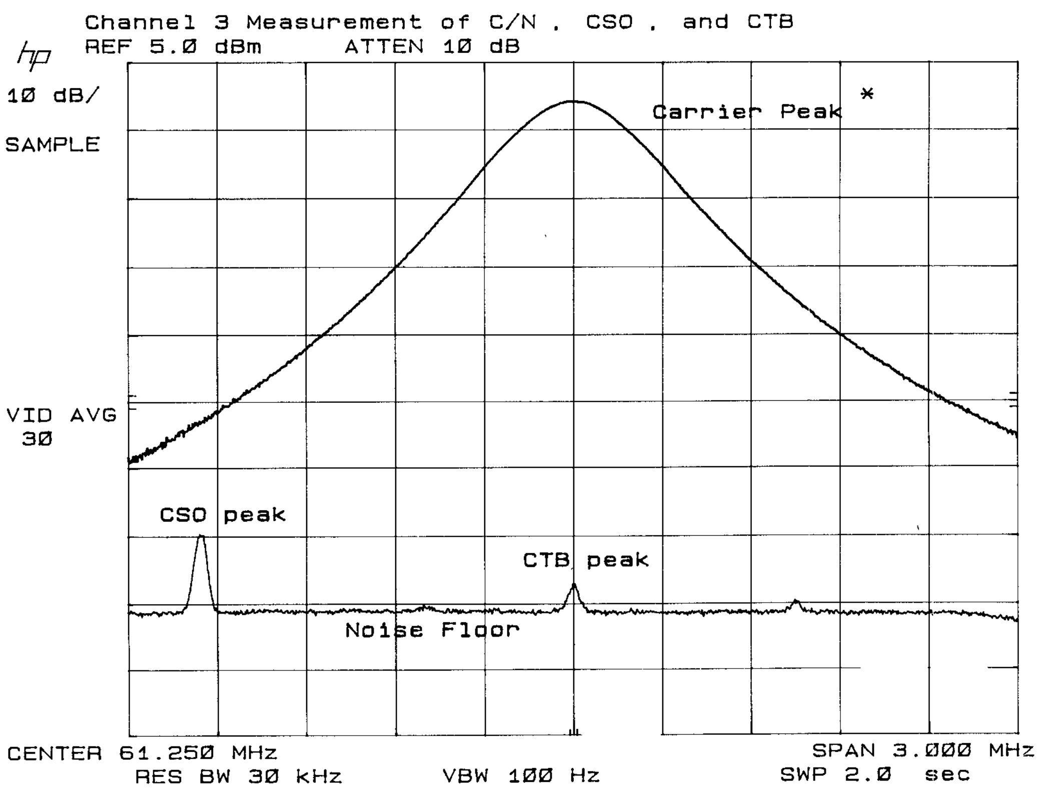


Fig. 7. Spectrum analyzer plot used to measure carrier to noise ratio CSO and CTB in channel 3.

TABLE I

#CH	42
$P_{trans,cw}$	+ 2 dBm optical
Modulation index	0.04 per channel
C/N(4 MHz)	51 dB
CTB	65 dBc
CSO	60 dBc
Noise Sources	
Shot Noise	13 pA/(Hz)$^{1/2}$
RIN	12 pA/(Hz)$^{1/2}$
Front End Noise	14 pA/(Hz)$^{1/2}$

The above values represent typical results and are not necessarily representative of system specifications or best achievable results.

distortion have been observed for cavities where the typical reflections are of the order of -20 dB.

III. Components

A. Laser

The noise and distortion requirements of AM analog systems have resulted in a preference for distributed feedback lasers (DFB's). We find that capped mesa buried heterostructure (CMBH) lasers [32] at 1.3 μm give excellent results. The fabrication process involves three epitaxial growths: a base structure grown on top of a grating by hydride VPE; blocking layers grown by MOCVD; and a final "cap" layer grown by hydride VPE. Base structures grown by hydride VPE have been shown to result in lasers with good slope efficiency [33]. MOCVD regrowth allows Fe-doped semi-insulating material to be used for current blocking layers. An antireflection coating is applied to the front facet and a high-reflectivity coating (65%) to the rear.

Fig. 9 shows the light–current characteristic of a typical laser, as well as the first derivative. These data were taken under pulsed excitation conditions to eliminate heating effects which are not important at CATV frequencies. Ideally, L' would be perfectly flat above threshold, but in all practical devices L' decreases at higher currents. In principle both the second- and third-order distortion of the device can be calculated from the $L-I$ curve. The CSO and the CTB in the ith channel can be obtained from

$$\mathrm{CSO}_i = \frac{\left(\dfrac{2L'^2}{L''L_0 m}\right)^2}{C_{i2}} \tag{5}$$

and

$$\mathrm{CTB}_i = \frac{\left(\dfrac{4L'^3}{L'''L_0^2 m^2}\right)^2}{C_{i3}} \tag{6}$$

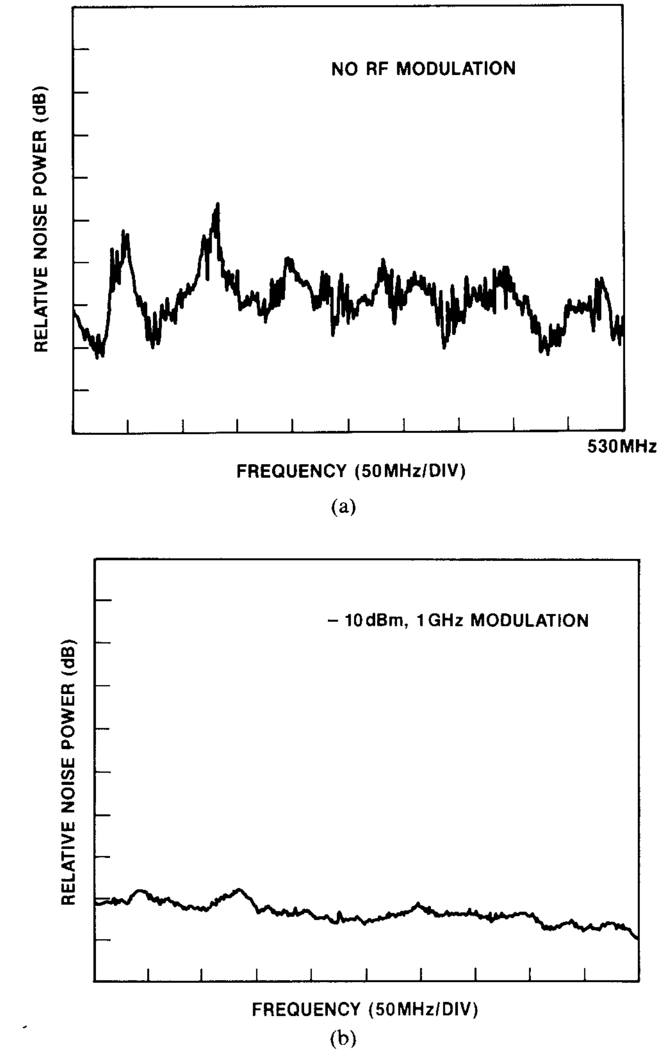


Fig. 8. (a) Noise spectrum of laser in the presence of optical feedback from a source located approximately 2 m from the laser. (b) Noise spectrum of the same laser, with RF input of -10 dBm at 1.0 GHz.

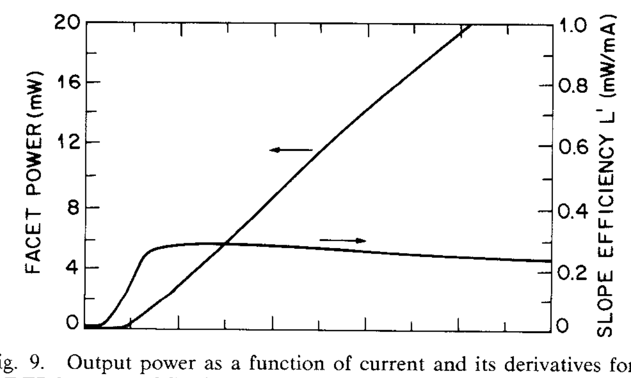


Fig. 9. Output power as a function of current and its derivatives for a DFB laser at 20°C. The drive current is produced in 10 μs pulses with a 0.1% duty cycle.

where $C_{i2,3}$ is the number of second- and third-order products in the ith channel respectively. In addition the power contained in a single second-harmonic tone of the form $2f$ in reflection to the carrier (2HD/C) is given by

$$\frac{\mathrm{2HD}}{\mathrm{C}} = 20\log\left(\frac{mL''L_0}{4L'^2}\right) \quad \mathrm{dBc}. \tag{7}$$

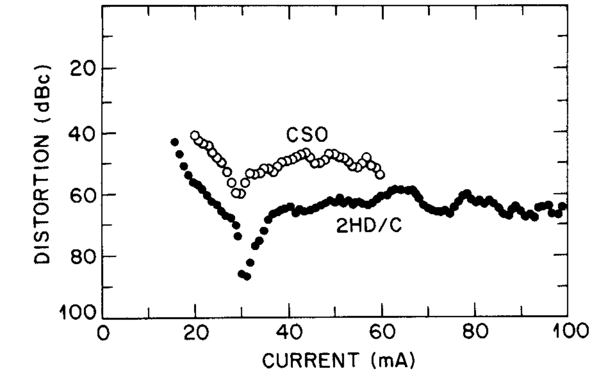


Fig. 10. Measured CSO versus bias current as compared with 2HD/C as calculated from the $L-I$ characteristics of the same laser assuming a modulation index of 0.04.

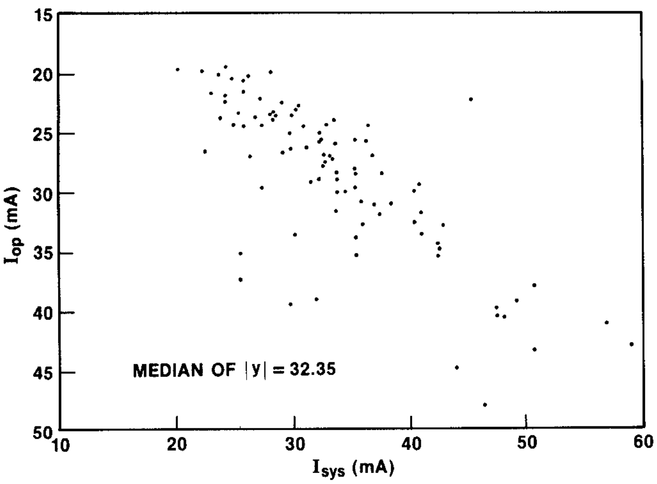


Fig. 11. The current at which $L''=0$ (I_{op}) versus the current at which CSO is minimized (I_{sys}) for a sample of 108 devices.

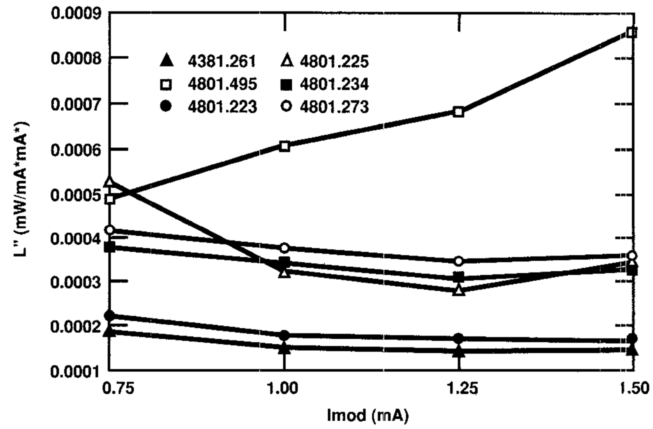


Fig. 12. Calculated L'' versus the modulation current, I_{mod}, for six devices.

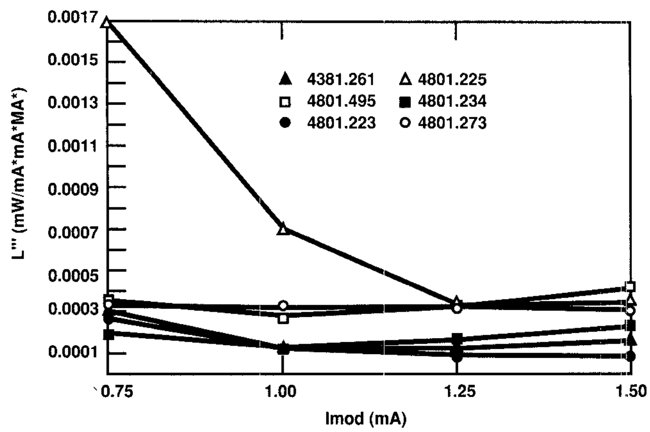


Fig. 13. Calculated L''' versus I_{mod} for six devices.

Equation (7) predicts that the second-order distortion vanishes where $L''=0$. Operation in the neighborhood of this point is observed to provide nearly optimum performance with respect to CSO. Fig. 10 shows the measured CSO in channel 3 for a 42 channel system and the calculated 2HD/C for the same laser. A modulation index of 0.04 per channel is assumed in the calculation. The correspondence between the current at which the best CSO is obtained (I_{sys}) and the current (I_{op}) at which $L''=0$ is close but not exact. A correlation plot of I_{sys} versus I_{op} is presented in Fig. 11. It emerges that the contribution of the fourth-order terms to the distortion causes a calculable elevation of current at which the CSO is optimized and may explain the observed results. In addition, the proximity of threshold to the operating current can be a significant source of distribution. The root mean square modulation index, u, can be written as

$$u = m\left(\frac{N}{2}\right)^{1/2}. \quad (8)$$

It can be shown that the composite distortion will exceed -60 dBc for $u > 0.24$ [34]. This effect can also be responsible for forcing operation at higher current. Finally, in actual applications the laser is biased at an operating point well above threshold. This causes a small systematic rise in the junction temperature relative to the temperature at which the pulsed $L-I$ curves of Fig. 9 were taken. These temperature differences may be partially responsible for the shift in the best operating point.

It is also important to determine if both the second- and third-order distortions at I_{sys} scale as predicted from (5) and (6). To assess the validity of these scaling rules an experiment was performed in which both CSO and CTB were measured as a function of modulation current, I_{mod}. From the measured CSO and CTB, values for both L'' and L''' were calculated from (5) and (6). It is important to note that neither L'' nor L''' can be easily measured in the neighborhood of I_{sys} because L'' is nearly zero and L''' is greatly influenced by measurement noise. In Figs. 12 and 13, we plot L'' and L''' respectively, as calculated from the measured CSO and CTB, as a function of I_{mod}. Data from six devices are presented. Some variation of L'' is observed, indicating that the second-order distortion is not exclusively determined by L'' at the system operating point. Again the influence of fourth-order distortion may be inferred. For five/six devices, and within measurement error, the calculated L''' is nearly independent of I_{mod}, indicating that there are no significant contributions that are not accounted for in (6). This may be consistent with the observation that the value of L''' is not changing rapidly in the vicinity of I_{sys}.

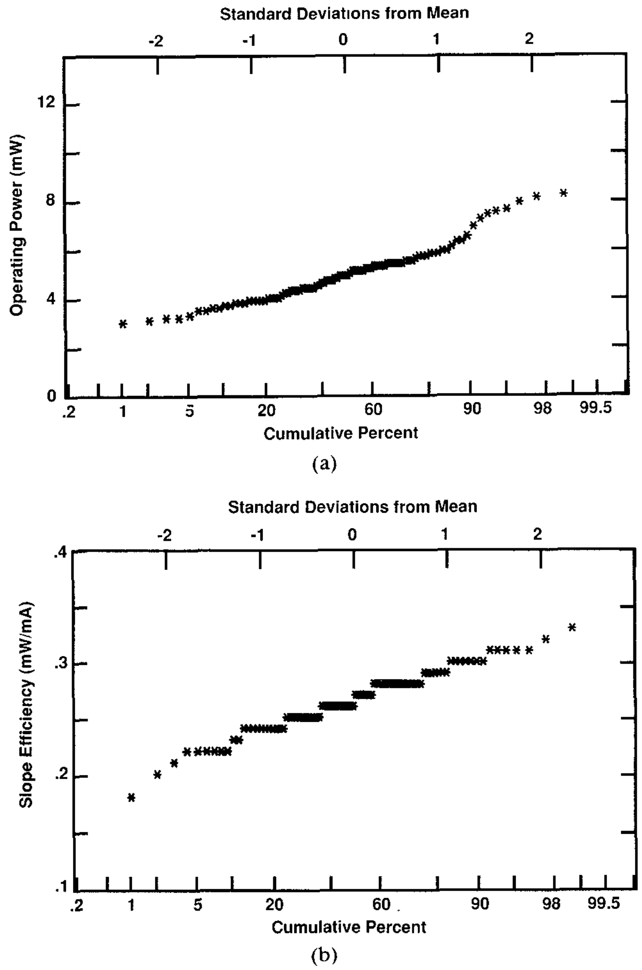


Fig 14. Normal probability distributions at 20°C and I_{op} for (a) facet power and (b) slope efficiency.

The preferred DFB lasers for analog applications possess $L-I$ characteristics similar to that shown in Fig. 9, and may operate at facet powers > 8 mW. Distributions of the output power and slope efficiency are shown in parts (a) and (b) of Fig. 14.

DFB lasers also have significantly better noise performance than Fabry–Perot lasers. Single-mode lasers exhibit RIN only a few dB above the shot noise limit. Lasers used in this project typically have RIN values of -152 dB/Hz at 200 MHz. Under similar operating conditions the RIN of Fabry-Perot lasers is from 5 to 10 dB poorer (an observation which may be influenced by near-in reflections in practical optoelectronic packages). As expected, the RIN decreases at high power, which provides another reason for striving for increased laser power.

B. Laser Module

The laser module employed is a standard Astrotec™ package of the type used in high-speed digital telecommunications. A microlensed fiber is used for optical coupling. In this particular application it is easy to demonstrate that high coupling efficiency, CE, is important. For systems dominated by laser noise, shot noise, and receiver noise, C/N scales as m^2, $L_0 m^2$, and $L_0^2 m^2$, respectively. Because both L_0 and the derivatives of L with respect to I scale directly with CE, we find that CSO scales as CE^0, CE^1, and CE^2 for the laser noise, shot noise, and receiver-dominated noise, respectively, and for fixed C/N. Similarly, CTB scales as CE^0, CE^2, and CE^4, respectively. Slope efficiencies for these laser modules average > 0.10 mW/mA.

Finally, it is appropriate to consider whether the composite distortions scale properly with the number of contributing products. In Fig. 15, a normal probability plot of the difference in CSO between channels 3 and 12 is presented for a large number of devices. A typical difference of 1.3 dB is observed, whereas the difference in the number of products is 7 dB. Clearly, some frequency dependence of the second-order nonlinearity can be inferred. A normal probability plot of the difference between CTB in channels 3 and 12 is presented in Fig. 16. The typical difference is 2.3 dB, which is in reasonable agreement with an expected difference of 3 dB based on product count.

C. Optical Isolator

The optical isolator used in these systems has been previously described [35]. The device is polarization independent, has a typical isolation of 30 dB at room temperature, a typical insertion loss of 1.2 dB, and a typical return loss > 60 dB.

IV. SUMMARY

In summary, we have demonstrated that the rigorous signal quality objectives associated with the CATV trunking application can, in principle, be satisfied with lightwave technology. With our best lasers, we have succeeded in transmitting 42 carriers over 12 km of fiber while maintaining a C/N of 52 dB and composite distortions < -70 dBc. These results are close to the fundamental limits established by shot noise and distortion due to statistical clipping [35]. For the most part, the behavior of these lasers is reasonably well predicted from the $L-I$ characteristics and from product count considerations. Initial studies of component reliability, with regard to both noise and distortion, have provided encouraging results; however, a detailed review is beyond the scope of this paper.

The current transmission technology is suitable for CATV trunking applications because the cost of an individual link may be shared over > 500 subscribers. Economic studies have shown that the cost of AM lightwave hardware is often (but not always) less than that of conventional alternatives for system upgrades. Furthermore, the degradations to signal quality encountered in the distribution part of the CATV plant typically account for roughly 50% of the total degradation. In consequence, improvements in the trunking plant have a bounded impact on the improvement observed by the subscriber. Further reductions in noise and distortion are still clearly productive. This is especially so if one considers the more stringent signal quality objectives for HDTV; however,

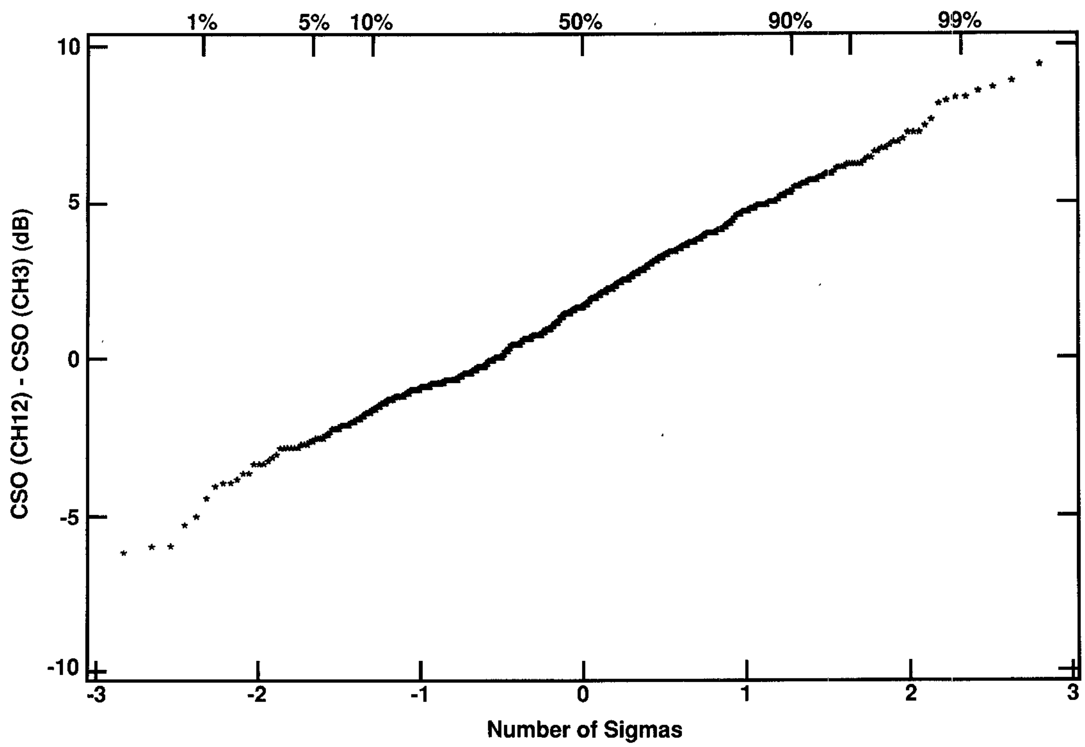


Fig. 15. Normal probability plot of the difference between CSO in channel 12 and channel 3 (700 devices).

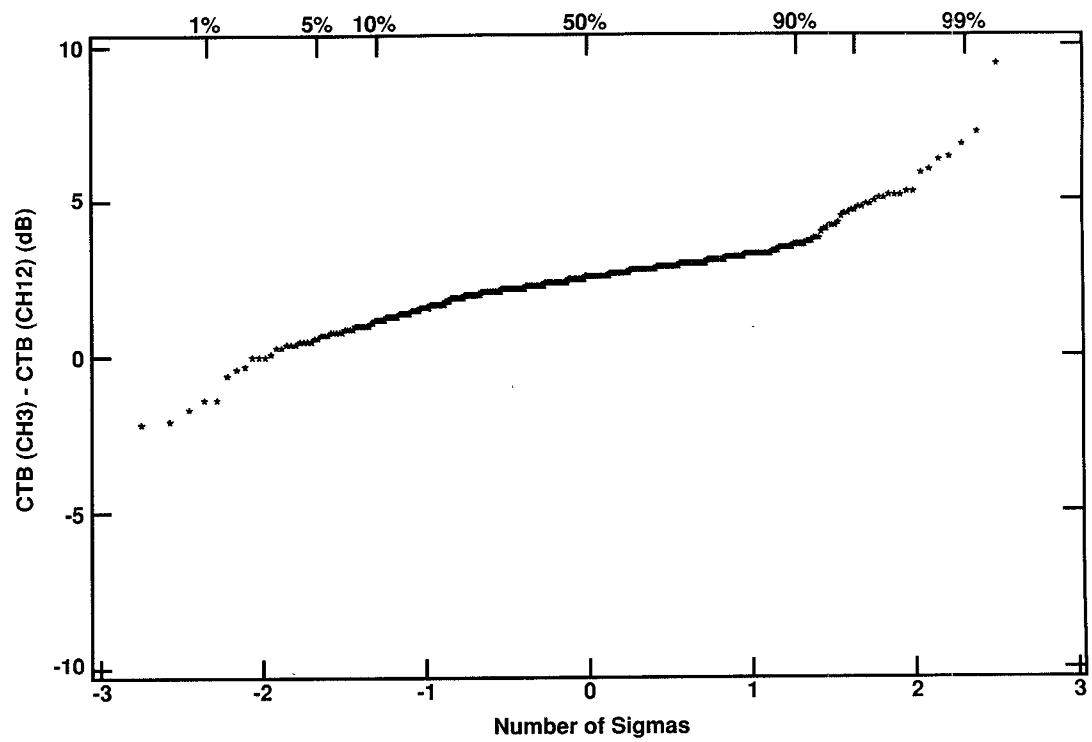


Fig. 16. Normal probability plot of the difference between CTB in channel 3 and in channel 12 (700 devices).

because further penetration into the distribution plant depends on radical reductions in cost, this must be a major focus for further work.

Acknowledgment

The authors gratefully acknowledge the guidance of T. E. Darcie in establishing their technical direction. They also acknowledge the highly significant contributions of J. Fayewicz and K. Weidner in establishing appropriate manufacturing procedures.

References

[1] T. Ohtsuka *et al.*, "Digital optical CATV system using hubbed distribution architecture," *J. Lightwave Technol.*, vol. 6, p. 1728, 1988.

[2] T. E. Darcie *et al.,* "Wideband lightwave distribution system using subcarrier multiplexing," *J. Lightwave Technol.*, vol. 7, p. 997, 1989.
[3] P. Hill and R. Olshansky, "Twenty channel FSK subcarrier multiplexed optical communication system for video distribution," *Electron. Lett.*, vol. 24, p. 1196, 1987.
[4] L. Linell, "A wideband local access system using emerging technology components," *IEEE J. Select. Areas Commun.*, vol. SAC-4, p. 612, 1986.
[5] G. Hayward, L. Linell, D. Mahoney, and L. Smoot, "A broadband ISDN local access system using emerging technology components," in *Proc. Int. Switching Symp.*, 1987, p. 597.
[6] J. R. Stern *et al.,* "Passive optical local networks for telephony applications and beyond," *Electron. Lett.*, vol. 23, p. 1255 1987.
[7] T. E. Darcie, "Subcarrier multiplexing for multiple-access lightwave networks," *J. Lightwave Technol.*, vol. LT-5, p. 1103, 1987.
[8] J. E. Bowers, "Optical transmission using PSK modulated subcarriers at frequencies to 16 GHz," *Electron. Lett.*, vol. 22, p. 1119, 1986.
[9] R. Olshansky and V. A. Lanzisera, "60-channel FM video subcarrier multiplexed optical communication system," *Electron. Lett.*, vol. 23, p. 1196, 1987.
[10] W. Way *et al.,* "Multichannel FM video transmission using traveling wave amplifiers for subscriber distribution," *Electron. Lett.*, vol. 24, p. 1370, 1988.
[11] K. Fujito, T. Uno, T. Ichida, and H. Serizawa, "Low noise wideband analog optical link using a DFB laser diode," in *Tech. Dig. Opt. Fiber Commun. Conf.* (OSA/IEEE, New Orleans), 1988, paper THO1.
[12] J. P. Franckart, T. Boeckx, J. M. Gilliard, D. Guevar, and E. Vion, "Analog transmission of TV channels on optical fibers with nonlinearities correction by regulated feedforward," in *ECOC Proc.*, 1983, p. 347.
[13] R. E. Patterson, J. Straus, G. Blenman, and T. Witkowicz, "Linearization of multichannel analog optical transmitters by quasi-feedforward compensation technique," *IEEE Trans. Commun.*, vol. COM-27, p. 582, 1979.
[14] M. Betelsmeier and W. Zschunke, "Linearization of broadband optical transmission systems by adaptive predistortion," *Frequenz*, vol. 38, p. 206, 1984.
[15] Y. Ueno and M. Kajitani, "Color TV transmission using light emitting diode," *NEC Res. Develop.* no. 35, p. 15, 1974.
[16] For a complete overview of CATV trunk requirements and measurement techniques, see *NCTA Recommended Practices for Measurements on Cable Television Systems*, 1st ed. National Cable Television Association, 1983.
[17] J. M. Senior, *Optical Fiber Communications: Principles and Practices* (Prentice-Hall International Series in Optoelectronics). Englewood Cliffs, NJ: Prentice Hall, 1985. Contains a general treatment of analog fiber transmission alternatives.
[18] Y. Yamamoto, "AM and FM quantum noise in semiconductor lasers—Part 1: Theoretical analysis," *IEEE J. Quantum Electron.*, vol. QE-19, p. 34, 1983.
[19] Members of the Technical Staff, Bell Telephone Laboratories, *Transmission Systems for Communications*, 5th ed., 1982.
[20] K. Simon, "The fundamentals of distortion in CATV amplifiers," Jerrold Electronics Corp., 1967.
[21] K. Y. Lau and A. Yariv, "Intermodulation distortion in a directly modulated semiconductor injection laser," *Appl. Phys. Lett.*, vol. 45, p. 1034, 1984.
[22] T. E. Darcie, R. S. Tucker, and G. J. Sullivan, "Intermodulation and harmonic distortion in InGaAsP lasers," *Electron. Lett.*, vol. 21, p. 665, 1985.
[23] R. W. Tkach and A. R. Chraplyvy, "Regimes of optical feedback in 1.5 micron distributed feedback lasers," *J. Lightwave Technol.*, vol. LT-4, p. 1655, 1986.
[24] H. Temkin, N. A. Olsson, J. H. Abeles, R. A. Logan, and M. B. Panish, "Reflection noise in index guided InGaAs lasers," *IEEE J. Quantum Electron.*, vol. QE-22, p. 286, 1986.
[25] T. Sugie and M. Saruwatari, "Distributed feedback laser diode to single mode fiber coupling module with optical isolator for high bit rate modulation," *J. Lightwave Technol.*, vol. LT-4, p. 236, 1986.
[26] E. Brinkmeyer, "Analysis of the backscattering method for single-mode optical fibers," *J. Opt. Soc. Amer.*, vol 70, p. 1010, 1982.
[27] A. F. Judy, J. A. Aberson, and G. F. Deveau, "Field measurements of return loss of ferrule-based mechanical splices," in *Proc. 37th Int. Wire and Cable Symp. (IWCS)*, Nov. 15, 1988, p. 586.
[28] A. F. Judy, "Intensity noise from fiber Rayleigh backscatter and mechanical splices," presented at 15th European Conf. Opt. Commun. (ECOC '89), Gothenburg, Sweden, Sept, 10, 1989.
[29] M. M. Choy, J. L. Gimlett, R. Welter, L. G. Kazovsky, and N. K. Cheung, "Interferometric conversion of laser phase noise to intensity noise by single-mode fiber optic components," *Electron. Lett.*, vol. 23, p. 1151, 1987.
[30] T. E. Darcie and G. E. Bodeep, "Lightwave subcarrier CATV transmission systems," pp. 524–533, this issue.
[31] A. Olsson, *Opt. Lett.*, to be published.
[32] J. Zilko, *et al., IEEE J. Quantum Electron.*, vol. 25, pp. 2091–2096, Oct. 1989.
[33] J. Blaha, K. K. Strege, and L. A. Gruezke, *IEEE J. Quantum Electron.* (to be published), Eleventh Semiconductor Laser Conf. Proc., 1988.
[34] A. A. M. Saleh, "Fundamental limit on number of channels in subcarrier multiplexed lightwave CATV system," *Electron. Lett.*, vol. 25, p. 776, 1989.
[35] W. L. Emkey *et al.,* "In-line pigtailed polarization-independent optical isolator," in *Tech. Dig. Conf. Opt. Fiber Commun.*, (IEEE/OSA, Houston), 1989, paper THF2.

Jan Lipson earned the B.S. degree in physics from the California Institute of Technology in 1972 and the Ph.D. degree in physics from the University of California, San Diego, in 1978.

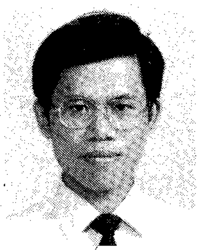
From 1978 to 1982, he was a member of the technical staff at Los Alamos National Labs, developing optical diagnostics for fusion energy plasmas. Since joining AT&T Bell Laboratories in 1982, he has specialized in the design of active and passive devices for both digital and analog lightwave transmission systems, and has authored 20 papers in the field. He is currently Development Manager for lightwave CATV components in the Lightwave Device Laboratory of AT&T Bell Laboratories and is responsible for the development of a wide spectrum of components and subsystems for broad-band distribution, and analog CATV.

Mr. Lipson is a member of the American Physical Society and the Optical Society of America.

L. Chainulu Upadhyayula (M'70–SM'82) received the B.Sc. degree in physics and the M.Sc. degree in applied physics from Andhra University, India, in 1955 and 1958, respectively, and the Ph.D. degree in engineering from Brown University in 1968.

During the period 1958–1959 he was trainee in the Atomic Energy Establishment, Bombay, India. From 1959 to 1964, he worked in the Atomic Energy Establishment on nuclear electronic instrumentation. From 1964 to 1967, he was a research and teaching assistant in engineering at Brown University, where he studied electrical transport properties of semiconductors. During the period 1968–1969 he was a postdoctoral fellow in engineering at Brown, studying tunneling through superconducting metal–insulator–metal structures at cryogenic temperatures. In 1969, Dr. Upadhyayula joined the Microwave Technology Center at RCA Laboratories, Princeton, NJ, as a Member of the Technical Staff. His work at RCA included 4–16 GHz GaAs transferred-electron (Gunn) amplifiers, high-efficiency IMPATT's, 18–40 GHz InP oscillators and amplifiers, transferred-electron logic devices, gallium arsenide field-effect transistors (FET's), gallium indium arsenide insulated-gate FET's, high-speed logic circuits, and microwave monolithic integrated circuits (MMIC's). He was responsible for the development of GaAs MESFET and GaInAs MISFET technologies for MSI and LSI logic circuits working at clock rates above 1–2 GHz. The logic circuits studied included gigabit-sampling-rate analog-to-digital converters, programmable dividers, and pseudorandom code generators. From 1986 to 1988 he was a team leader of the MMIC group responsible for the design and development of MMIC digital phase shifters and gain blocks at *X*- and *Ku*-band frequencies. In April 1988, he joined AT&T Bell Laboratories as a member of the technical staff. He is presently involved in the study of laser nonlinearities and their analog modulation techniques at RF and microwave frequencies.

Dr. Upadhyayula has published several technical papers in these areas. He was awarded a General Telephone and Electronics Fellowship in 1967–1968 for his graduate study. In 1970, he received an RCA Laboratories Outstanding Achievement Award for team effort in the development of GaAs transferred-electron amplifiers. He holds 17 U.S. patents and has several disclosures pending. Dr. Upadhyayula is a member of Sigma Xi. He is very active in IEEE activities at the local as well as national level and is a past vice-chairman and chairman of the ED/MTT Chapter, Princeton Section. Since 1983 he has been serving on the Digital Microwave Systems Committee (MTTS-9) of the Microwave Theory and Techniques Society.



Sun-Yuan Huang (S'80–M'85) received the B.S. degree in physics from Chung Yuan University, Chungli, Taiwan, in 1973, the M.S. degree in applied physics from National Tsing Hua University, Hsinchu, Taiwan, in 1979, and the Ph.D. degree in electrical engineering from the University of California at San Diego, La Jolla, in 1985. His doctoral work involved the study of $LiNbO_3$ integrated optical circuits.

From 1985 to 1986 he was an Associate Professor at the National Tsing Hua University, where he taught a graduate course in quantum electronics. From 1986 to 1988 he was a Technical Staff Member at the Rockwell International Corporation, Dallas, TX, where he worked on the development of InGaAsP/InP distributed feedback semiconductor lasers, high-speed buried crescent lasers, and low-cost loop laser modules. In 1988 he joined the AT&T Bell Laboratories, Solid State Technology Center, Breinigsville, PA, as a Member of Technical Staff. His current work involves the development of CATV lightwave transmission systems.

Dr. Huang is a member of the OSA, Phi Tau Phi, and Chi Delta Kappa.

Charles B. Roxlo received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology in 1979, 1979, and 1981, respectively, all in electrical engineering. His doctoral thesis work was on optically pumped mode-locked semiconductor lasers.

From 1977 to 1979 he researched mercury halide laser kinetics at the Avco Everett Research Labs in Everett, MA. From 1981 to 1986 he was at the Exxon Corporate Research Labs in Clinton, NJ. His research there centered on the optical properties of materials, especially interfaces and surfaces. This included work on amorphous semiconductors and superlattices, organic semiconductors, and catalytic materials. In November 1986 Mr. Roxlo joined AT&T Bell Labs in Murray Hill, NJ, where he is involved in the development of semiconductor lasers. He is currently supervisor of the Semiconductor Laser Development Group.

E. J. Flynn was born in Miami, FL, on August 19, 1950. After graduating from Florida State University, in 1972, he began graduate work in physics at the University of Chicago. He received the Ph.D. degree in 1978 with thesis work in inelastic light scattering and joined Bell Laboratories, Murray Hill, NJ, the same year.

He has worked in semiconductor laser development since 1980. His current work addresses problems in electrical properties of buried heterostructure lasers and laser performance in analog systems.

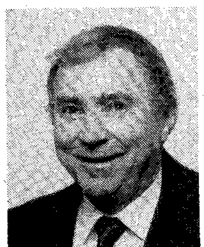
Paul M. Nitzsche was born in Plainfield, NJ, in 1963. He received the B.Sc. degree in physics from Fairfield University in 1985 and the M.Sc. degree from the Stevens Institute of Technology in 1989.

Since joining AT&T Bell Laboratories in 1985, he has worked in the Semiconductor Laser Development Department on high-frequency testing of laser diodes.

Carl J. McGrath received the bachelor of science degree from Cornell University in 1971. He received the master of engineering (electrical) degree, also from Cornell University, in 1972.

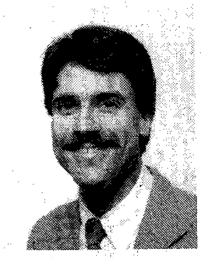
He is Supervisor of the CATV Lightwave Group at AT&T Bell Laboratories in North Andover, MA. He is involved in the systems engineering and design of AT&T's lightwave AM transmission products. He joined Bell Laboratories in 1972. Prior responsibilities were development of high-speed interfaces for synchronous digital lightwave systems, development of maintenance and operations support interfaces for long haul lightwave systems, and development of DS1 to DS3 cable carrier systems. From 1976 to 1978 he was an Operations Supervisor with New England Telephone, responsible for maintenance and operations planning for digital cable carrier networks.

Mr. McGrath is a member of SCTE.



Gerald L. Fenderson received the bachelor of science degree in electrical engineering from the University of Maine in 1960 and the master of science degree in electrical engineering from Northeastern University in 1963.

He is a Distinguished Member of Technical Staff in the CATV Lightwave Group at AT&T Bell Laboratories in North Andover, MA. He is a design engineer for AT&T's AM fiber-optic transmission project. He joined Bell Laboratories in 1960. Prior assignments were design engineering for analog and digital microwave radio systems. He was a member of the design team for the Metrobus high-speed digital fiber-optic transmission system.



Mark S. Schaefer holds the B.S.E.E. degree from Rutgers University and the M.S.E.E. degree from Stanford University.

He is a Distinguished Member of Technical Staff in the CATV Lightwave Group at AT&T Bell Laboratories in North Andover, MA. He performs systems engineering and circuit development for AT&T's AM fiber-optic transmission project. He joined Bell Laboratories in 1979. Prior assignments were circuit and system development for the Metrobus synchronous lightwave system, circuit development for DS3 asynchronous digital multiplex products, and design and analysis for T-carrier repeater products.