Lightwave Subcarrier CATV Transmission Systems

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Abstract —We describe the design and performance of multichannel AM-VSB lightwave CATV systems. Requirements on linearity and noise are derived, and factors limiting the performance of the laser transmitters and receivers are discussed. For high-performance lasers the carrier-to-noise ratio and composite second- and third-order distortions are acceptable for video trunk systems. Impairments because of fiber reflections and dispersion and mode partition fluctuations in the laser are discussed. Feedforward, feedback, and predistortion are discussed, but difficulties with each prevent immediate application. Finally, the use of $LiNbO_3$ external modulators and high-power solid-state lasers is considered. The third-order distortion and insertion loss of the modulator more than counteract the high available laser power (100 mW), making this alternative unattractive unless a third-order linearizer can be implemented.

I. Introduction

The LARGE bandwidth and low loss of optical fibers have led to a telecommunications revolution in long-haul, data networking, and fiber feeder applications. Extremely rapid market penetration has been possible in these applications where the cost per unit of bandwidth can support the cost of the lightwave components. However, for applications other than these high-end systems, the acceptance of fiber has been slow. This is especially true in video distribution systems, where the cost per bandwidth must be much lower than that of a telecommunications system. In an attempt to reduce this cost, several video distribution systems have been proposed using digital [1]–[3] or frequency-modulated (FM) [4], [5] subcarrier modulation (SCM). SCM takes advantage of the large modulation bandwidth of semiconductor lasers and the availability of microwave components, and provides a convenient technique for multichannel video transmission. Unfortunately, the large bandwidths (30 to 100 MHz per channel) and the required conversion from analog to digital or FM format restrict the use of these systems to high-end video supertrunking applications. The ideal solution is to eliminate the format conversion and transmit the same multicarrier video spectrum used by the cable television (CATV) industry. If the requirements for linearity and noise can be met at a reasonable cost, then this simple system could open a large new market for lightwave technology.

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Meeting these linearity and noise requirements is not an easy task for lightwave technology, which has been used predominantly for robust digital transmission. Amplitude-modulated (AM) vestigial-sideband (VSB) video CATV signals require a carrier-to-noise ratio (CNR) near 50 dB for ideal picture quality. This CNR is much larger than the 20 dB required for digital or FM systems, and this difference is balanced only partially by the small 4 MHz per channel bandwidth. We show later that this CNR requirement restricts the available loss margin limiting span lengths (< 20 km) and restricting the amount of passive division that can be tolerated. The many distortion products generated by laser or receiver nonlinearity must have a cumulative power that is less than -50 dBc. Only recently have developments in laser fabrication technology led to performance that is acceptable for CATV systems.

In this paper we discuss the design and performance of lightwave AM-VSB multicarrier CATV systems. Linearity and noise requirements are discussed in Section II. Specific factors that limit the linearity of directly modulated semiconductor lasers are discussed in Section III and considerations for receiver design are presented in Section IV. The compromise between CNR and distortion, together with results from a system using a 1.55 μm DFB laser, are presented in Section V. Finally, several system impairments and alternatives to direct current modulation are discussed in Sections VI and VII.

II. System Requirements

There are two potential applications for AM-VSB CATV lightwave systems, shown in Fig. 1, with slightly different requirements. CATV operators are looking to fiber to improve the quality, capacity, and reliability of the trunks systems that connect their head-end facilities to remote distribution nodes. These links currently use coaxial cable and dozens of electronic amplifiers. Typical lengths are 10 to 20 km and quality is of the utmost importance. Telephone operating companies are aggressively pursuing fiber-to-the-home (FTTH) systems to meet expected future demand for capacity. Video is clearly the most likely source of this future demand.

For either application the transmission quality can be described by three standard test parameters, which are obtained using a "MATRIX generator" (MG) and a standard test procedure [6]. This MG simulates the video

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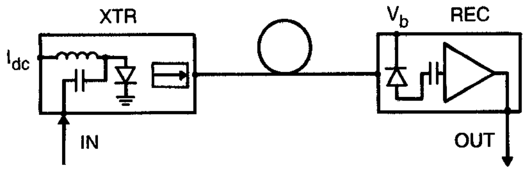

Fig. 1. Lightwave CATV system using direct modulation of the laser bias current. I_{dc} and V_b are the laser bias current and bias voltage on the p-i-n photodiode. The laser is coupled to a single-mode fiber through an optical isolator (arrow).

TABLE I

	TRUNK	FTTH
Distance (km)	10-20	1-2
Number of Channels	40-80	30-40
CNR (dB)	55	48
CTB (dBc)	-65	-55
CSO (dBc)	-55	-50

carriers of up to 80 channels by passively combining the outputs of crystal-controlled oscillators. The test procedure makes it possible to measure the carrier-to-noise ratio (CNR), composite triple beat (CTB), and peak or composite second-order (CSO) distortion. The CNR is the ratio of the carrier to the total noise power in 4 MHz bandwidth. The CTB and CSO are the ratios of the carrier to the total power within the largest accumulation of third- and second-order distortion products, respectively, within each channel. As described later in this section, the distribution of these products depends on the exact channel frequency allocation plan used, and each quantity varies for different channels. It is then up to the system designer to define what levels for which channels are acceptable. Typical values for trunk and FTTH systems are presented in Table I. For the trunk system, high fidelity is guaranteed by the strict specifications. The FTTH specifications allow a considerable reduction in performance, hence cost, but do not noticeably degrade picture quality. Tests performed using the MG produce distortion results that are worse than those that would be obtained using real modulated video carriers. Since the video carriers are unmodulated for the MG tests, and since modulation reduces each video carrier by 5.7 dB, CSO and CTB results quoted for MG tests would improve by approximately 6 and 9 dB, respectively, if a multichannel live video source were used.

Noise from the receiver, shot noise, and relative intensity noise (RIN) from the laser limit the CNR. For a total received photocurrent I_o and an optical modulation depth per channel m, the CNR in a channel of bandwidth B is given by [7]

$$\mathrm{CNR} = \frac{(I_o m)^2}{2B\left[n^2 + I_o^2\left\{\mathrm{RIN} + \frac{2e}{I_o}(1-\eta)\right\}\right]} \tag{1}$$

where the preamplifier equivalent input noise current is n (typically 15 pA/$\sqrt{\mathrm{Hz}}$ for a 75 Ω amplifier), e is the electronic charge, and η is the coupling efficiency between the laser output facet and the photodetector ($0 < \eta < 1$). The term involving η, which is often neglected, is required from the original definition of RIN [8], [9], which includes shot noise and excess amplitude fluctuations normalized for perfect coupling ($\eta = 1$). Fig. 2 shows the strong dependence of CNR on m, and that for typical operating parameters, the CNR is not far from the quantum limit. This quantum limit, in which shot noise is the only impairment, is given by

$$\mathrm{CNR}_o = \frac{I_o m^2}{4eB}. \tag{2}$$

Increasing m improves the CNR but also increases distortion, such that the optimum operating point is a compromise. The values for CTB and CSO depend on the number and magnitude of the distortion products generated. Laser nonlinearity is the dominant limitation and the magnitudes of the resultant products are discussed in Section III. The number and distribution of products can be calculated, for a given frequency allocation plan, by summing over all possible combinations of two and three channels, for second- and third-order, respectively [7]. Table II lists the

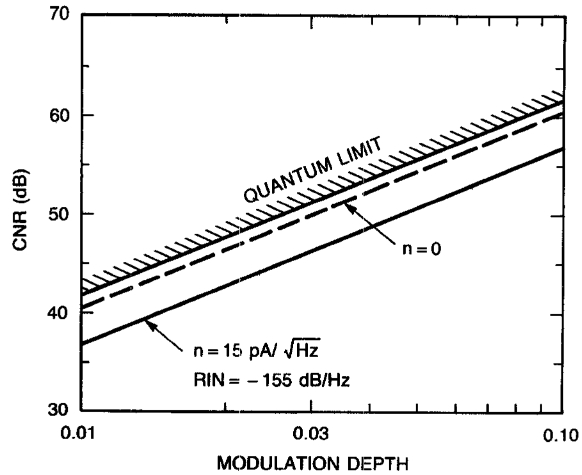

Fig. 2. Carrier-to-noise ratio (CNR) versus modulation depth for typical laser intensity noise (RIN) = −155 dB/Hz and receiver noise current $n = 15$ pA/$\sqrt{\mathrm{Hz}}$. The quantum limit assumes that shot noise is the only impairment.

TABLE II
PRODUCT COUNTS

CHANNEL	FREQ (MHz)	NUMBER OF CHANNELS 30	42	60
SECOND ORDER				
3	61.25	14	26	44
12	199.25	3	7	25
40	319.25	-	12	12
THIRD ORDER				
3	61.25	123	285	663
12	199.25	225	525	1110
40	319.25	-	372	1120

number of second- and third-order products that determine the CSO and CTB for various channel loads and the standard U.S. CATV frequency plan, without considering A-1, A-2, $\cdots$ channels in the FM band. These numbers are dominated by products of the type $f_i \pm f_j$ and $f_i \pm f_j \pm f_k$, for second- and third-order, respectively, and allow estimation of the allowable magnitude of each type of product, as measured by a simple two-tone linearity test. To approximate the linearity requirements for trunk systems, the laser must have a second-harmonic distortion (2HD/C) less than -70 to -80 dBc and a two-tone third-order distortion (3IM/C), of the type $2f_i \pm f_j$, less than -95 to -105 dBc. Meeting these requirements, but with a modulation depth that can provide an acceptable CNR, has proven to be feasible, but difficult.

III. Laser Linearity

Distortion generated by modulation of the light intensity has been the most difficult impairment to overcome. Of the many intensity-modulation (IM) techniques that could be used, such as external modulators and interferometric conversion of frequency modulation (FM) to IM, direct current modulation has provided the best performance to date. In this section the nonlinear processes that limit direct current modulation are discussed.

Distortion in semiconductor lasers has been the subject of many investigations. Harmonic [10], [11] and intermodulation distortion [12]–[14] in AlGaAs and InGaAsP lasers has been calculated and measured, motivated primarily by improving the capability of high-speed microwave SCM systems. Since these high-speed systems operate in the multi-GHz frequency range, the frequency-dependent distortion that results from the nonlinear coupling between the photons and the injected carriers is the dominant problem. This same nonlinear coupling is responsible for the relaxation oscillation that limits the modulation bandwidth of the laser. Hence the distortion caused by this interaction is called resonance distortion (RD).

RD is well understood and can be described by a small-signal analysis that is justified completely for CATV applications. Without repeating the expressions presented in [13], it can be seen from Fig. 3, for a laser with a 7 GHz resonance frequency, that the rapid decrease of RD with decreasing frequency leaves a window of low RD just wide enough for the CATV requirements. Similar results apply for two-tone second-order products [15]. Although in the U.S. the CATV frequency band does not extend past 550 MHz, if problems caused by RD are to be avoided, laser resonance frequencies greater than about 7 GHz are required. Reducing the resonance frequency shifts the curve on Fig. 3 to the left such that RD increases over the band of interest. Fortunately, for the high-performance lasers required to give suitable power and linearity, the resonance frequency generally exceeds 7 GHz. There remains some ambiguity on the exact mechanism that is responsible for damping the relaxation oscillation, and the second-order distortion near half the resonance frequency, where 2HD/C is maximum, and at low frequency, where it is minimum, differs for different mechanisms. This uncertainty is shown by the shaded region in Fig. 3 [16]. Regardless of the mechanism responsible (nonlinear gain from spatial hole burning [17]–[19], two-photon absorption [20], carrier heating [21], or spectral hole burning [22]), the resulting distortion should not interfere with CATV operation.

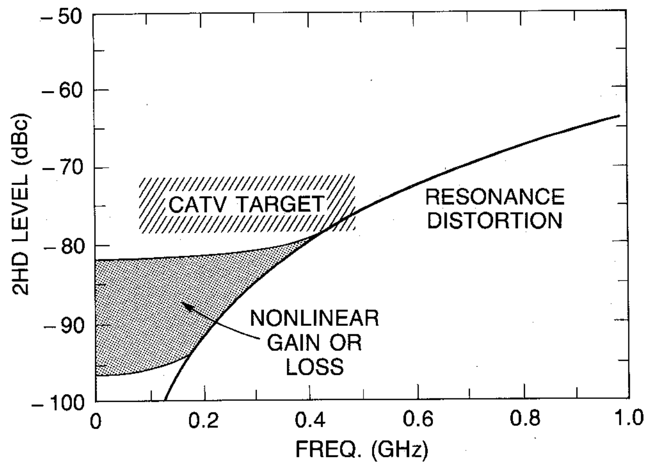

Fig. 3. Frequency dependence of second-order distortion for directly modulated laser with a modulation depth of 0.04 and a resonance frequency of 7 GHz, compared to specifications for CATV systems. Leakage currents contribute a wide range of distortion depending on the effectiveness of the current confinement structure.

Within the window of low RD, several other nonlinear mechanisms must be considered. These include current leakage [23], intervalence band absorption [24], [25], and free-carrier absorption [26]. Two types of current leakage can occur. Imperfections in the blocking structure generally lead to shunt current leakage wherein the current through the active layer is reduced to a nonlinear fraction of the total injected current. The amount of distortion from shunt leakage varies considerably for different device structures. Leakage also occurs when carriers escape from the heterojunction by diffusion from the edges of the active region to the cladding layers. Although this diffusion is not normally significant in InGaAsP lasers, it may be responsible for the small distortions obtained from laser structures that have been made specifically for low shunt leakage. Both types of leakage can be incorporated into a laser rate equation analysis by making the active layer current a nonlinear function of the total injection current. Using this approach, it has been shown that the second-order distortion in channel-substrate buried-heterostructure (CSBH) lasers is due entirely to shunt current leakage [27]. However, the blocking layers in these CSBH lasers are poor compared to the capped-mesa buried-heterostructure (CMBH) lasers. Intervalence-band absorption, which has been shown to be partially responsible for the temperature dependence of the laser threshold [25], introduces nonlinearity because of the strong dependence of absorption on carrier density. Free-carrier absorption, although comparable in magnitude to intervalence-band absorption, should be linearly proportional to the carrier density [26] and therefore less effective at producing distortion.

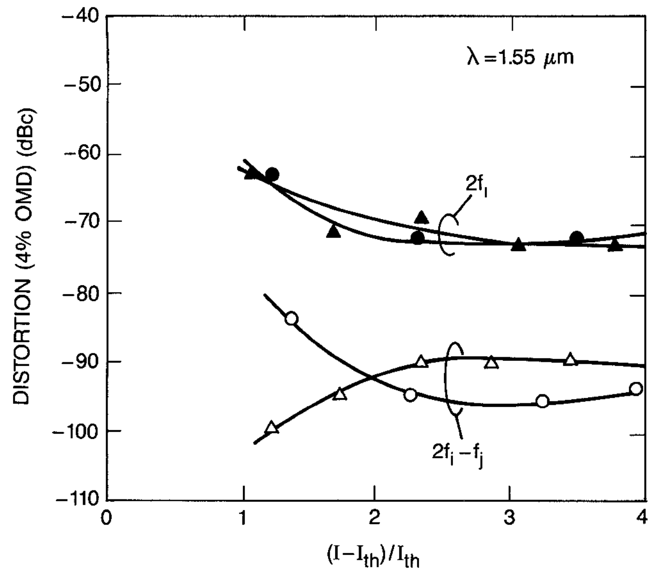

Fig. 4. Second harmonic and two-tone third-order intermodulation distortion for two 1.55 μm DFB lasers. The dotted lines are the levels required for acceptable system performance.

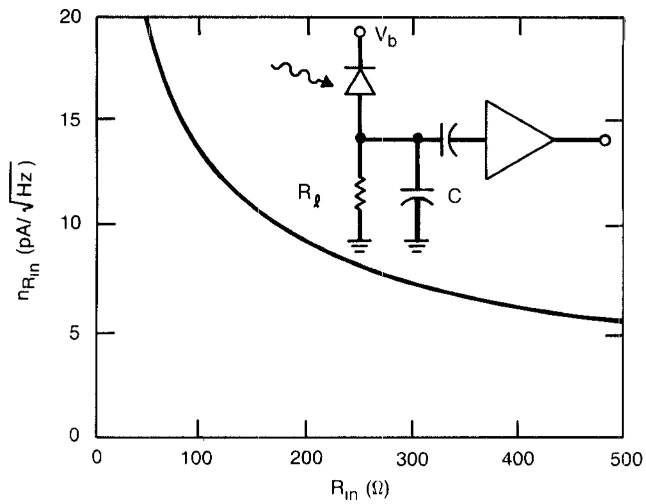

Fig. 5. Noise contributions for voltage preamplifiers (insert) showing the effective input current noise for load resistor R_l.

Even the best lasers can produce unacceptable distortion levels as the result of optical reflections or feedback. Optical reflections may cause nonlinearity within the laser itself [28] or may produce interferometers within the fiber that interact with laser chirp to convert the FM to IM [29]. The former is eliminated using optical isolators and the latter can be minimized if reflections from all device facets and fiber ends are minimized.

Finally, if all the aforementioned sources of laser distortion are eliminated, then the maximum modulation depth is limited by clipping. If the $L-I$ characteristics are perfectly linear with current above threshold, distortion introduced by infrequent excursions of the current to values less than zero, for which the light output is clipped at zero, limits the modulation depth per channel to about 0.05, for a CNR of 55 dB [30]. This fundamental limit suggests that continued improvements in device linearity will result in only slight increases in the usable modulation depth, and that the primary source of performance improvement must then be in increasing the laser output power.

As mentioned in the previous section, to meet the trunk system requirements for CSO and CTB, the lasers must produce second-harmonic distortion and two-tone third-order intermodulation distortion in the vicinity of −75 and −100 dBc, respectively, although these values vary depending on the exact system specifications. Fig. 4 shows these distortions for two 1.55 μm CMBH DFB lasers, at an optical modulation depth of 4% per tone. Both the second- and third-order distortion are marginally acceptable over a broad range of bias currents. The system performance of these lasers is discussed later.

IV. Receivers

Receivers for lightwave CATV systems differ significantly from receivers for digital lightwave systems. First, the total received optical power is about 1 mW, which is several orders of magnitude greater than that for a digital system. Second, the receiver must provide extremely linear response while providing a CNR of more than 50 dB. Fortunately the simplest receiver, which consists of a p-i-n photodiode coupled to a conventional CATV amplifier (PIN–AMP), works well.

Noise introduced by the PIN–AMP is best described by an equivalent input current noise n, which is typically near 15 pA/$\sqrt{\text{Hz}}$. This leads to a CNR as defined by (1). In considering alternative types of receivers, it is useful to compare equivalent input noise currents from various sources. We first consider coupling the photodiode to an FET or other voltage amplifier, as shown in Fig. 5. Current generated in the p-i-n develops a voltage across the resistor R_l which is amplified by the voltage amplifier. The total input capacitance C is the sum of the capacitances of the p-i-n, the transistor, and any parasitic capacitance associated with interconnections. If the only noise source is Johnson noise from the resistor, then the CNR can be written, by analogy with (1), as

$$\text{CNR}_R = \frac{(m \cdot I_o)^2 R_l}{8kTB} \tag{3}$$

where kT is 0.026 eV at $T=300$ K. Comparing (1) with (2) gives an equivalent input current noise from R_l:

$$n_{R_l}^2 = \frac{4kT}{R_l}. \tag{4}$$

This noise current is shown in Fig. 5 as a function of R_l. If the noise performance is to be much better than that of the PIN–AMP, which is about 15 pA/$\sqrt{\text{Hz}}$, as expected from a 75 Ω input impedance, then R_l must be increased significantly. For conventional lightwave systems, where the received signals are much weaker, R_l can typically be increased to 1 kΩ. However, for the large signals received in a CATV system and for large R_l, the voltage excursions across the resistor exceed the linear operating range of most transistor amplifiers. A PIN–FET receiver with an effective R_l of 300 Ω may improve the CNR by a factor of

4, but may also introduce additional distortion, depending on the exact characteristics of the transistor.

One can also consider the effect of the input capacitance, which reduces the voltage developed at the input for increasing frequencies. If the transistor has a noise spectral density given by

$$S_a = \frac{4kT\Gamma}{g_m}\left[\frac{V^2}{Hz}\right] \tag{5}$$

where Γ is typically 1.1 for GaAs FET's, g_m is the transconductance, and noise from R_l is neglected, then the frequency dependence of the CNR is given by

$$CNR_a = \frac{(m \cdot I_o)^2}{2S_a B(\omega C)^2}. \tag{6}$$

Alternatively, the equivalent input current noise is

$$n_a^2 = S_a(\omega C)^2. \tag{7}$$

Equation (7) shows that for a total input capacitance of 2 pF, the worst noise that would be generated at the highest frequency in the CATV band is about 4 pA/$\sqrt{Hz}$; with lower capacitance, noise from R_l is a more important concern.

One could also consider using an inductor to counteract the capacitive roll-off and create a resonant impedance match between the p-i-n and the transistor. It can be shown [31] that a series-resonant PIN–FET, designed to maximize the CNR to the highest frequency required, would reduce the amplifier-induced current noise by a factor of 3 over the nonresonant receiver. But here again one must be concerned about the voltage range required at the transistor. Effective impedance matching reduces the input noise, but places stronger demands on the linearity of the preamplifier.

V. System Performance

Since the performance of a system is determined almost entirely by the linearity, power, intensity noise, and coupling efficiency of the laser, the most impressive system results are obtained through effective optimization of these qualities. The resulting performance, as shown through commercially available systems [32], can meet the strict specifications for the trunk market. In this section, rather than attempting to reproduce this high performance, we describe the relative significance of the various noise contributions and the trade-off between CNR and distortion.

Measurements were conducted on a 42 channel system consisting of 10 km of fiber, a 1.55 μm DFB CMBH laser, and a PIN–AMP receiver. The 1.55 μm lasers were used primarily because of availability and do not have any intrinsic advantage over 1.3 μm lasers for CATV applications. The reduced fiber loss (near 2 dB for 10 km spans) for 1.55 μm wavelengths is offset by reduced coupling efficiency and laser output power. The laser was coupled to the fiber using a lensed fiber that was fusion-spliced to an optical isolator. The coupling loss between the output facet of the laser and the detector was 11 dB. Fig. 6 shows the measured CNR as a function of laser bias current for a

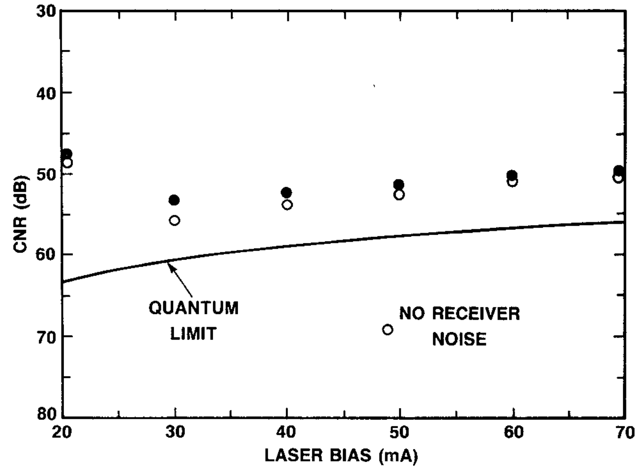

Fig. 6. CNR versus laser bias current for 10 km, 1.55 μm wavelength system and constant input RF power. CNR is 53 dB between 30 and 40 mA bias.

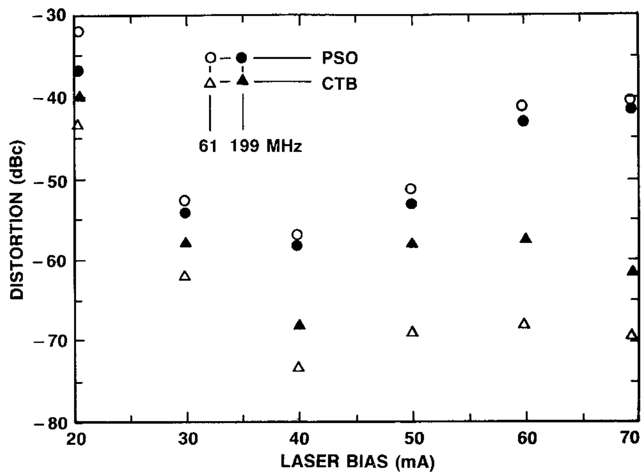

Fig. 7. CSO and CTB for two channels with the operating conditions of Fig. 6, for two channels. Best linearity is obtained near 40 mA bias, where both parameters are within required values.

constant input RF power. For low bias currents, the modulation depth per channel (m) is near 0.07 and for 70 mA, m is reduced to 0.02. The maximum CNR, for bias currents between 30 and 40 mA, is 53 dB. Independent measurements of the RIN for this laser agree with values derived from the system performance, which are near −152 dB/Hz. Given this level of RIN, the degradation of the CNR caused by receiver noise is less than 2 dB. Decreasing the RIN to the quantum limit would improve the CNR to better than 60 dB, which would allow increasing the 10 km span.

Under the same system conditions, the measured CTB and CSO for two channels are shown in Fig. 7. Both quantities meet the trunk specifications for bias currents near 40 mA. For higher currents, distortion resulting from the $L-I$ sublinearity becomes dominant, even though the modulation depth is small. All lasers exhibit this problem at high currents, and as a result, the capability of many laser structures to provide output powers of many tens of milliwatts cannot be used in CATV systems. It is useful to

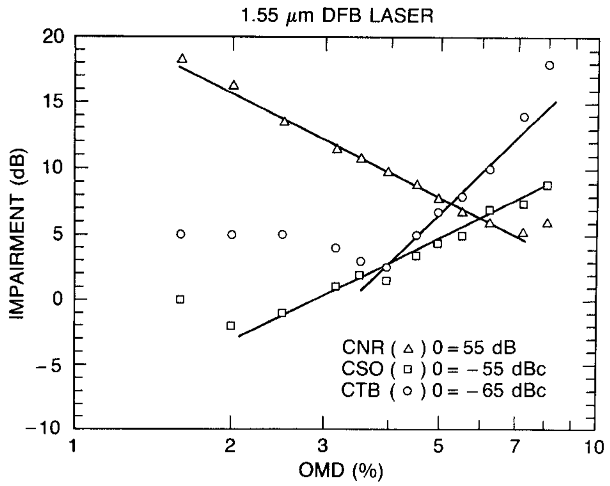

Fig. 8. Dependence of CNR, CSO, and CTB on modulation depth, normalized to specifications for a trunk system, for a 1.55 μm DFB laser. Solid lines are fit using predicted dependence on modulation depth.

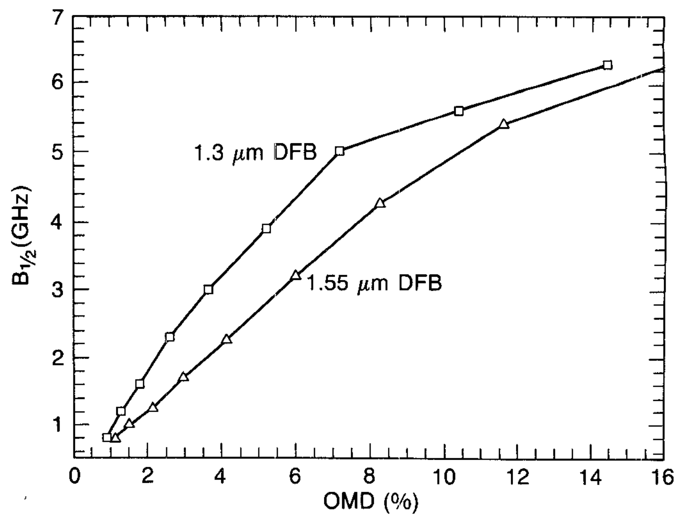

Fig. 9. Half width of optical spectrum for 1.3 and 1.55 μm DFB lasers as a function of modulation depth for 42 channels. The half width is linear with modulation depth of small signals.

plot the CNR, CSO, and CTB as a function of the modulation depth, as shown in Fig. 8. Each quantity is normalized to specifications that might be typical for trunk systems, with positive impairments being undesirable. The data points were measured for the same system described above, but using a laser with slightly poorer performance. The CNR improves with the square of the modulation depth, as expected from (1), except for large m, where the excessive distortion interferes with the CNR measurement. Since the ratio of second-order distortion to the carrier (optical intensity) is proportional to m [13], the CSO (RF power) is proportional to m^2. Also as expected, the CTB is proportional to m^4. Both the CTB and the CSO deviate from the expected behavior for m values smaller than 0.03 and larger than 0.07. For small m, the additional distortion may result from weak reflections from the isolator that become a problem when the coherence length of the modulated laser output becomes large. For large m, the additional distortion is caused by clipping at the laser or nonlinearity in the receiver. Within the useful operating range, the trade-off between good noise performance and good linearity suggests an optimum m near 0.05. The exact optimum point depends on how the user weights each of the three sources of impairment and on the exact specifications of each, but for the laser at 40 mA bias, third-order distortion would appear to be the limiting problem. In actuality, the CTB is a problem only because the coupled output power is insufficient to provide a good CNR for modulation depths closer to 0.04, where the CSO and CTB are equal.

VI. System Impairments

In addition to the problems of laser linearity and noise, several other phenomena can impair transmission quality. The most serious of these are the result of fiber dispersion or reflections. In addition to increasing distortion and noise generated by the laser, multiple fiber reflections create interferometers which result in the conversion of the modulation-broadened optical spectrum into interferometric intensity noise (IIN). Although mode partition fluctuations do not produce excessive intensity noise at the output facet of the laser, dispersion introduces propagation delays that convert the fluctuations into laser mode partition noise (LMPN). These two impairments are described briefly in this section.

IIN has been investigated previously for digital systems [33], [34] and, in part, for CATV applications [35]. The noise results from the mixing on the photodetector of the received signal with a weak delayed signal that has undergone multiple reflections. If the polarizations of both signals coincide (worst case), then the generated RF noise spectrum contains a total power that is proportional to the product of the direct and reflected powers. The impairment that results depends on the fraction of this total noise power within each channel, which can be calculated if the spectrum of the modulated optical signal is known. Previous calculations [35] have assumed that this spectrum is Lorentzian. However, it can be shown [36] that if clipping is avoided and the spectrum is dominated by FM rather than IM, then the optical spectrum is Gaussian with a half width that is proportional to the FM efficiency (GHz/mA) and the modulation depth. For a 42 channel load and $m = 0.04$, a typical half width is 4 GHz, as shown in Fig. 9. If the reflections are separated by more than the coherence length (several cm), the detected beat-noise spectrum is also Gaussian, but with a half width increased by a factor of $\sqrt{2}$. The frequency dependence of the noise spectrum is then not significant, since the CATV band overlaps the flat low-frequency portion of the Gaussian, and it can be shown that for two reflections, with reflectivities R_1 and R_2,

$$\mathrm{CNR} = \frac{\sqrt{2\pi}}{8} \frac{m^2}{R_1 R_2} \frac{B_{1/2}}{B} \tag{8}$$

where $B_{1/2}$ is the half width of the optical spectrum and B

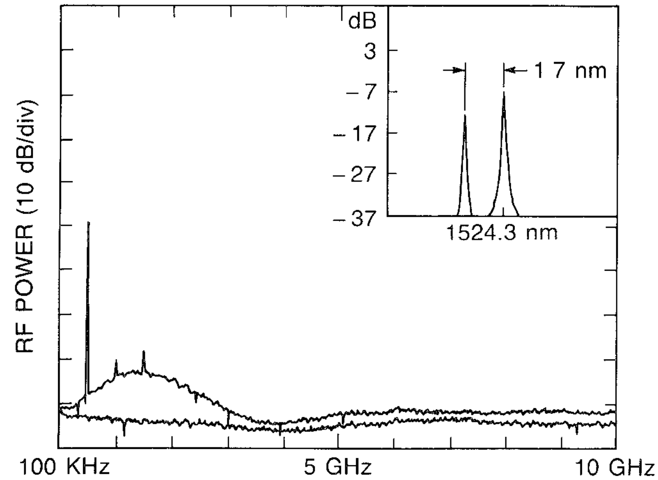

Fig. 10. Detected RF spectrum for 42 channel/and 10 km of fiber system but with a 1.55 μm DFB laser with side mode (insert). Noise near 500 MHz has equivalent magnitude of -128 dB/Hz. Signal at 500 MHz and harmonics result from intensity modulation from a single channel. Lower trace is receiver noise floor.

is the noise bandwidth of the channel (4 MHz). Equation (8) predicts that reflectivities greater than -30 dB limit the CNR to 60 dB. Poor splices should not be used in the CATV network. Also, Rayleigh backscatter can produce effective reflectivities of -32 dB for long lengths of fiber [35]. Even without reflections from splices, the IIN from this backscatter could limit the CNR, especially if the source spectral width is small.

LMPN, which can be an important source of noise in high-speed digital systems [37], can also be a problem in CATV systems using multimode lasers with wavelengths well away from the dispersion zero. Different propagation delays for each mode of a multimode 1.55 μm laser result in a received intensity noise spectrum that contains a wealth of information about the statistics of the partition events but is useless for CATV systems [38]. If standard fiber is replaced by dispersion-shifted fiber, the noise is reduced but not entirely eliminated. For standard fiber, LMPN also restricts the use of 1.55 μm DFB lasers with weak side modes. A laser with a single weak side mode results in a noise spectrum of the type shown in Fig. 10. The noise exhibits a null at a frequency that corresponds to the reciprocal of the dispersive delay between the two modes [38]. The impairment to the CNR can be described by an effective intensity noise that near 500 MHz (Fig. 10) is -128 dB/Hz.

VII. Alternatives

Many alternatives have been investigated with the objective of overcoming the difficulties encountered with direct current modulation, but none have been exploited commercially as of this date. The most attractive alternative is to use external intensity modulators to modulate recently available diode-pumped Nd:Yag lasers. Several attempts have been made to use active predistortion, feedback, or feedforward to ease the linearity requirements for directly modulated lasers and external modulators. These alternatives are discussed in this section. One can also use wavelength-division multiplexing (WDM) or multiple fibers to assemble more capable systems from less capable components, but since these do not affect the capabilities of the individual components, these will not be discussed here.

A. External Modulators

The use of external modulators is limited by two problems. First, CATV systems do not have enough loss margin to allow the addition of a component that has significant insertion loss. $LiNbO_3$ intensity modulators have an insertion loss that is rarely less than 3 dB and is typically 5 dB, which is comparable to the system margin for commercially available trunk systems. Second, the interferometric conversion of phase difference to intensity modulation leads to light-versus-voltage ($L-V$) characteristics that are inherently nonlinear, whereas the $L-I$ characteristics of directly modulated lasers are inherently linear. The recently proposed digital optical switch [39] may have improved linearity, at the expense of drive voltage, but this remains to be demonstrated. Nevertheless, the possibility of exploiting the high power (>100 mW) and low noise of diode-pumped Nd:YAG lasers makes modulator-based systems potential contenders. Considerable effort has therefore been directed toward characterizing the linearity of $LiNbO_3$ modulators [40].

Although the $L-V$ characteristics are nonlinear, the point of inflection in the $L-V$ curve offers a bias point for which the second-order distortion is zero. This can be realized in practice, but depends critically on bias voltage and input polarization. Unfortunately, the third-order distortion is 30 dB worse than that measured for good directly modulated lasers at the same modulation depth. System measurements have shown that the CTB performance for a complete multicarrier load is indeed as poor as expected from the discrete-tone measurements [41]. Theoretical analyses of the modulator linearity [42] confirm this behavior and show that a modulation depth of greater than 0.02, for an ideal modulator, will result in unacceptable third-order distortion. Any imbalance or difference in loss between the two arms of the interferometer leads to further degradation of the CTB [43], which explains why predicted performance is slightly better than that obtained experimentally.

Fig. 11 compares the power budget for systems using externally modulated YAG lasers for those using directly modulated diode lasers. We assume YAG output powers of 100 mW, and a coupling loss of 2 dB from the YAG to the fiber. For the diode laser, the output power is taken as the median facet powers of 300 commercial systems [32], which is 5 mW, and a coupling efficiency of 50%.

Fig. 12 presents the CNR for the two configurations in Fig. 11, as calculated using (1), as a function of modulation depth. We assume a receiver current noise of 15 pA/$\sqrt{\text{Hz}}$ and RIN values of -152 dB/Hz for both systems, in agreement with measured values for DFB lasers and man-

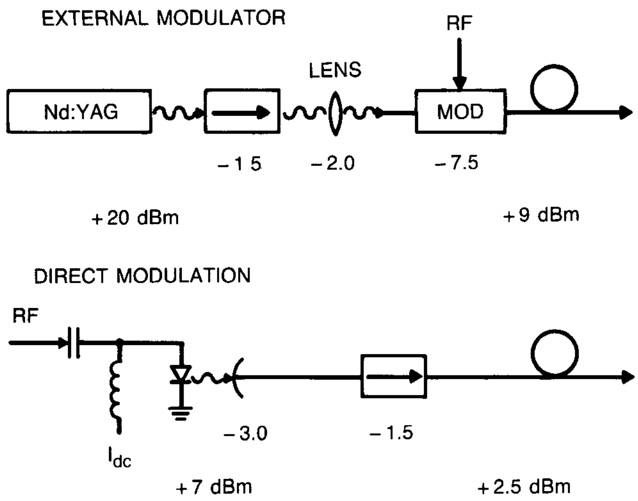

Fig. 11. Power budget for modulator-based system compared to system using direct modulation.

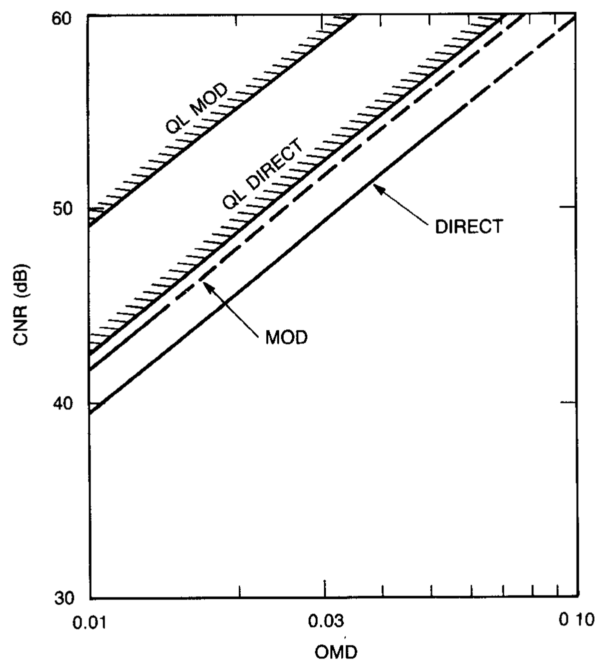

Fig. 12. Comparison of CNR for modulator-based and directly modulated systems shown in Fig. 11. Dotted lines show modulation depths for which acceptable linearity can be obtained.

ufacturers' published data for the YAG lasers.[1] The additional received power makes little difference in the received CNR. As long as the CNR is limited primarily by RIN, the only factor affecting the CNR is the modulation depth. For the same modulation depth, the CNR for the direct modulation is 2 dB lower than that for the modulator because of noise contributions from receiver noise and shot noise. Fig. 12 also shows the quantum limits for both systems. The system using the modulator operates 8 dB from being shot-noise limited (eq. (2)), whereas the direct system is within 3 dB. Although one could add 6 dB worth of system margin and make the two CNR's equal, for the same m, one could not increase m for the modulator to more than 0.02. The broken lines in Fig. 12 represent the limits on m. Reducing the RIN for the YAG laser makes the modulator approach more attractive. If the RIN from the YAG was shot noise only and if other system-related intensity noise sources were not a problem, then the YAG at $m = 0.02$ would outperform the DFB at $m = 0.04$.

Another possible problem with external modulation is that the coherence of the modulated light is much higher than it is for directly modulated diode lasers. Interferometric intensity noise (IIN) (Section VI) may then become a more severe limitation. For the directly modulated DFB lasers, the half width of the optical spectrum was typically 4 GHz, whereas for an externally modulated YAG laser the spectrum information is broadened to twice the information bandwidth (two-sided spectrum). For the DFB, the beat noise arising from fiber reflections was distributed over 6 GHz, whereas for the YAG it is distributed over less than 1 GHz. The actual spectrum of multipath noise is complicated and, depending on the coherence length, not all of the spectrum will produce interference. But the portion that does interfere will be concentrated within the CATV band, and could present problems.

B. Linearization

Considerable work has been done on linearizing lasers or external modulators using feedforward, feedback, or active predistortion techniques. If external modulators are to be useful, then some linearization must be used to allow increasing the modulation depth to near 0.04.

Electro-optic feedback can, in principle, provide reductions in distortion and noise that have been realized for years in electronic amplifiers. The difficulties with this approach are that the loop delay must be less than approximately 100 ps and the loop gain must be near 50 dB to overcome coupling losses and device efficiencies and provide net gain. To solve the problem of feedback loop delay, several feedforward schemes have been implemented for bandwidths considerably smaller than the CATV bandwidth [44], [45]. The distorted transmitted signal is detected and compared to the electronic input signal, and the resulting error signal is used to correct the transmitted signal either by remodulating the distorted signal with a second modulator or by adding a second directly modulated laser. The difficulty with feedforward is in generating an accurate error signal. Both feedback and feedforward linearizers may be possible, but they are both extremely difficult to implement.

With predistortion, as the name implies, the input signal is passed through a nonlinear element such that when the modified input signal is applied to the nonlinear transmitter, an undistorted signal results. Unlike the feedback and feedforward linearizers, the predistorter does not reduce intensity noise. It has, however, resulted in a net reduction of second-order distortion in a directly modulated 40–60 channel CATV system [46].

A schematic of a predistortion circuit is shown in Fig. 13. The input x is normally transmitted from the laser

[1] Measurements taken since the submission of this paper have shown that the RIN for the YAG laser may be as low as −165 to −170 dB/Hz.

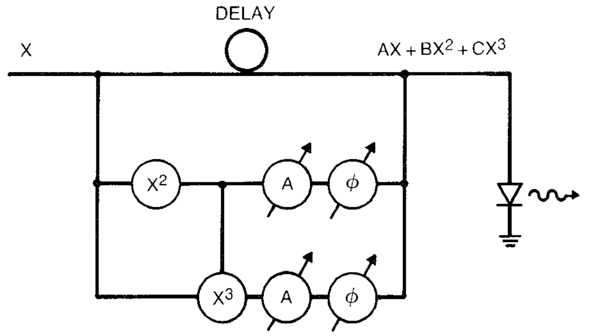

Fig. 13. Active predistorter for correction of second- and third-order distortion

such that the light output is a nonlinear function of x. If we assume that this nonlinear function can be represented by a polynomial series $ax + bx^2 + cx^3 + \cdots$, then this circuit adds nonlinear terms to the modified input x' so that the output is linear in x up to fourth-order. This circuit is difficult to execute, primarily because of the difficulty in designing acceptable analog multipliers. Alternatively, one could use a variety of nonlinear elements and attempt to adjust the properties of the predistorter to suit the particular nonlinearity of the transmitter, but without simultaneous control of both second- and third-order predistortion it is difficult to improve second-order without worsening third- and vice-versa. The circuit shown in Fig. 13 is potentially adaptable to arbitrary levels of both orders of distortion.

We constructed a second-order predistorter, shown by the upper branch of Fig. 13, and succeeded in achieving a net reduction of CSO without increasing CTB. The multiplier circuit consisted of a phase splitter and dual-gate MESFETS as nonlinear elements.[2] The phase splitter is used to generate inverted and noninverted signals which are used to minimize the unwanted fundamental and third-harmonic signals. Using this predistorter in a 60 channel system the CSO could be reduced by 17, 11, and 7 dB at channels 3, 11, and 40, respectively, with no change in the CNR or CTB [46]. However, this improvement could be obtained only for lasers with relatively large sublinearity of the $L-I$ characteristics, and little improvement was obtained for good lasers at the optimum bias current. This suggests that good lasers, at optimum bias, are limited by the frequency-dependent resonance distortion which cannot be corrected using our simple predistorter. Also, successful operation of the predistorter requires critical adjustment of the amplitude and phase of the squared signal. Slight changes in laser bias or temperature require changes of the correction signal. An adaptive circuit would be essential. Even though we obtained a slight improvement in CSO, the complexity of the circuit and the difficulty in maintaining the correct amplitude and phase make the usefulness of this technique questionable. Although one cannot rule out the possibility of designing a feedback, feedforward, or predistortion linearizer for CATV applications, the implementation of such a circuit appears most difficult. Yet without such circuits, the outlook for externally modulated systems is bleak and further efforts are required to design more linear devices for directly modulated systems.

[2]Circuit provided by B Glance and R. C. Giles

VIII. Conclusions

Recent improvements in the design and fabrication of semiconductor lasers have resulted in structures that can meet the strict linearity and noise requirements for CATV trunk systems. The elimination of several intrinsic laser nonlinearities leaves levels of distortion that can be tolerated, and for good lasers the modulation depth used is close to the maximum allowed by clipping. Further improvements in device linearity will then result in only slight improvements in system performance. Further device research is therefore directed towards increasing the usable laser output power and reducing cost.

Direct modulation of a high-performance laser appears to be the best approach when compared to several alternatives. This conclusion is supported by the recent commercial success of such systems. Systems that use external modulators and high-power solid-state lasers must contend with the insertion loss and nonlinearity of the modulator. Unless the modulation depth can be increased, which requires a reduction of third-order nonlinearity, these systems cannot compete with those using directly modulated lasers. Active linearization techniques may change this situation entirely, but several technical obstacles inhibit the implementation of these techniques.

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