Applications of Traveling-Wave Laser Amplifiers in Subcarrier Multiplexed Lightwave Systems

WINSTON I. WAY, SENIOR MEMBER, IEEE, CHUNG-EN ZAH, MEMBER, IEEE, AND TIEN-PEI LEE, FELLOW, IEEE

Abstract —Applications of traveling-wave laser amplifiers in subcarrier multiplexed lightwave systems, for the distribution of multiple channels of FM and AM-VSB video signals, are described. Both experimental results and a general analysis on the video carrier-to-noise ratio are presented. Other important system design considerations associated with using TWLA's are also discussed.

I. Introduction

SIGNIFICANT progress has recently been made in research on high-capacity subcarrier-multiplexed (SCM) lightwave systems, mainly as a result of increased interest in finding near-term, low-cost solutions for the distribution of multichannel TV services on fiber. The progress in subcarrier multiplexing technology has been greatly facilitated by advances in novel optoelectronic components, particularly in the areas of high-speed semiconductor lasers and photodetectors (with bandwidths of over 10 GHz) and laser amplifiers. The large bandwidth of the semiconductor laser enables many channels of analog [1]–[5] or digital RF signals [6], [7] to be frequency-division-multiplexed in the electrical domain. The composite signal can then be used to modulate the laser directly. Among the advantages of subcarrier multiplexing are simplicity in system design, ready availability of system components, and the possibility of offering different services without synchronization or coordination (since each service is carried by different RF frequencies). The capability of a subcarrier-multiplexed lightwave system can be further enhanced by incorporating one or more traveling-wave laser amplifiers (TWLA's) which provide additional system gain, either for increasing the span length or for power splitting in a broad-band distribution network. TWLA's are suitable for SCM systems because their wide bandwidth (40–50 nm) can accommodate several multi-longitudinal-mode lasers or a large number of DFB lasers, and they have high saturation output power (0 to 8 dBm).

In this paper, we will describe applications of TWLA's in subcarrier-multiplexed distribution systems for both frequency-modulated (FM) and amplitude-modulated vestigial-sideband (AM-VSB) video signal distribution. In Section II the characteristics of a 1300 nm facet-angled and antireflection-coated TWLA used in our experiments are described. Analytical carrier-to-noise ratio (CNR) characterizations of SCM systems employing TWLA's are given in Section III. Section IV and Section V describe experimental results of using TWLA's in multichannel FM and AM-VSB video signal systems, respectively. Section VI briefly describes the potential optical reflection problems associated with the residual reflectivities of optical fiber connectors/splices while using TWLA's. The paper is summarized in Section VII.

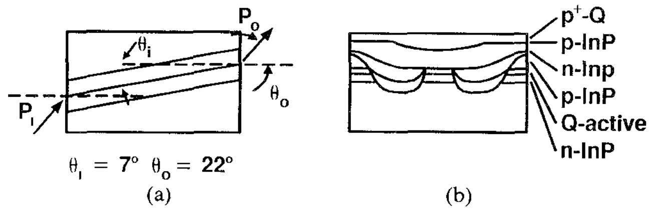

Fig. 1. Schematic of a traveling-wave laser amplifier with angled facets.

II. Laser Amplifiers

The laser amplifiers used in the experiments are made from 1300 nm GaInAsP/InP wafers grown by liquid phase epitaxy (LPE), with a double-channel planer buried heterostructure for current and optical confinements. TWLA's typically require low facet reflectivity ($\leqslant 10^{-3}$) to suppress the Fabry–Perot resonances. This, in general, requires tight control of the refractive indices and the thicknesses of antireflection coatings on the facets. We have, however, simplified the fabrication of near traveling-wave amplifiers by slanting the waveguide (gain region) from the cleavage plane such that the light reflected by the cleaved facets does not couple back into the waveguide (Fig. 1). This results in an effective modal facet reflectivity of about 0.5% without antireflection (AR) coating. The effective facet reflectivity is further reduced to $5\text{–}8\times10^{-4}$ by the application of AR coatings to both facets [8].

Fig. 2(a) shows the amplified spontaneous emission power spectrum of the amplifier at different bias currents. The TE-mode gain ripple near the gain peak wavelength of 1296 nm when the amplifier is biased at 110 mA is 2.5 dB with a free spectral range of 0.5 nm (Fig. 2(b)). In the present experiment, lensed single-mode fibers are used for coupling signal in and out of the amplifier along the

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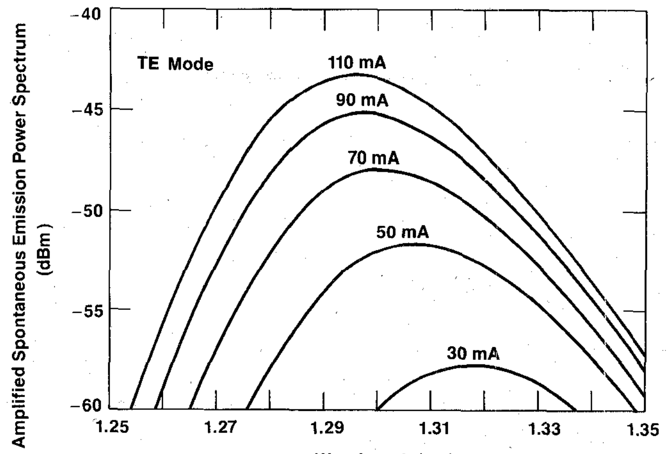
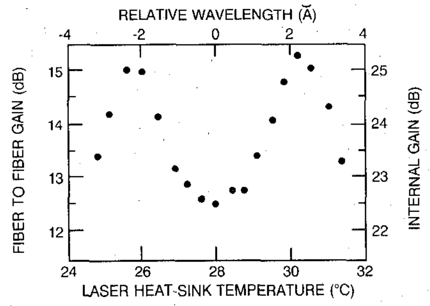


(a)



(b)

Fig. 2. (a) Amplified spontaneous emission power spectrum at various bias levels. (b) TE-mode gain ripple of TWLA biased at 110 mA. Signal wavelength is tuned by changing heat-sink temperature of 1.3 μm DFB laser. Fiber-to-fiber gain differs from internal gain by coupling loss of 5 dB/facet.

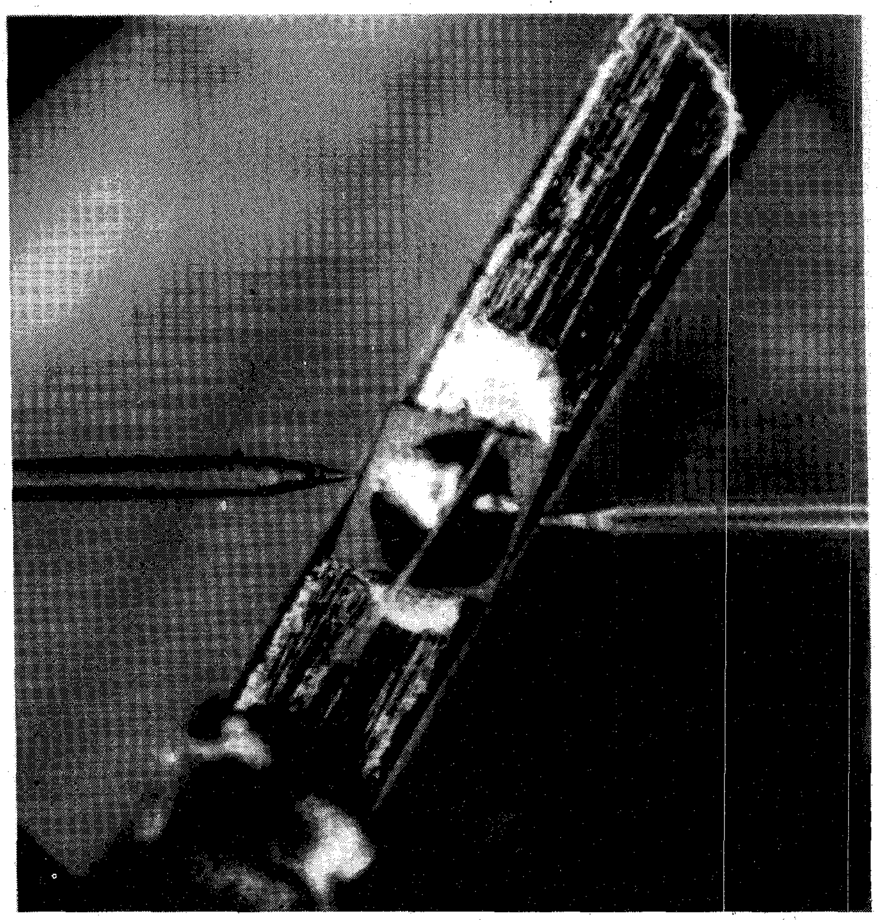


Fig. 3. The TWLA with lensed fibers for coupling light in and out.

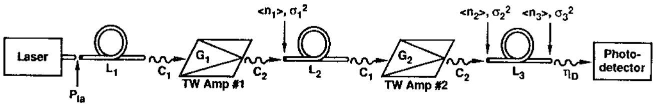


Fig. 4. Schematic of a lightwave system using two cascaded TWLA's.

direction of peak spontaneous emission intensity (Fig. 3). The coupling loss, including one biconic connector loss (~0.5 dB), is estimated to be about 5 dB per facet. At 100 mA, the fiber-to-fiber gain is measured to be about 12 ± 1.0 dB, corresponding to an internal gain of 22 ± 1.0 dB. The gain for the TM mode is 4 dB less than that of the TE mode. For the TE mode, the output saturation powers at an injection currents of 120 mA and 90 mA were measured at output facets to be 9.5 dBm and 8 dBm (4.5 dBm and 3 dBm into single-mode fiber), respectively. The 3 dB bandwidth of the signal gain is about 40 nm.

III. System Carrier-to-Noise Ratio (CNR) Analysis

In this section, we present a complete analysis which includes the coupling losses in and out of a TWLA, and is an extension of the one given in [9]. We first show the analysis of two cascaded stages of TWLA in subsection A and generalize the results to N stages in subsection B. Overall system CNR is summarized in subsection C.

A. Noise in Two-Stage TWLA's

As shown in Fig. 4, the mean values of photon numbers $\langle n_1\rangle$, $\langle n_2\rangle$, and $\langle n_3\rangle$ can be expressed respectively as follows (see Table I for definitions of mathematical symbols):

$$\langle n_1\rangle = \frac{P_{la}}{E}L_1C_1G_1C_2 + (G_1-1)C_2n_{sp}\cdot m_t\cdot\Delta f_1 \tag{1}$$

$$\langle n_2\rangle = \langle n_1\rangle L_2(C_1G_2C_2) + (G_2-1)C_2n_{sp}\cdot m_t\cdot\Delta f_1 \tag{2}$$

$$\langle n_3\rangle = L_3\langle n_2\rangle. \tag{3}$$

The variances of the photon numbers σ_1^2, σ_2^2, and σ_3^2 are given respectively as follows:

$$\sigma_1^2 = \frac{P_{la}}{E}L_1C_1G_1C_2 + (G_1-1)n_{sp}m_t\cdot\Delta f_1\cdot C_2 + 2G_1(G_1-1)n_{sp}\chi\frac{P_{la}}{E}L_1C_1C_2^2 + (G_1-1)^2n_{sp}^2\cdot m_t\cdot\Delta f_2\cdot C_2^2 \tag{4}$$

$$\sigma_2^2 = \langle n_1\rangle L_2C_1G_2C_2 + (G_2-1)n_{sp}\cdot m_t\cdot\Delta f_1\cdot C_2 + 2G_2(G_2-1)n_{sp}\chi(\langle n_1\rangle L_2)C_1\cdot C_2^2 + (G_2-1)^2n_{sp}^2\cdot m_t\cdot\Delta f_2\cdot C_2^2 \tag{5}$$

$$\sigma_3^2 = \left(\sigma_{1,\text{sig-sp}}^2 + \sigma_{1,\text{sp-sp}}^2\right)\cdot(L_2C_1G_2C_2L_3)^2 + \sigma_{2,\text{shot}}^2\cdot L_3 + \left(\sigma_{2,\text{sig-sp}}^2 + \sigma_{2,\text{sp-sp}}^2\right)\cdot L_3^2. \tag{6}$$

According to (1)–(6), the spectral current density of the received total shot noise $\langle i_{\text{shot}}^2\rangle$, the signal–spontaneous emission beat noise $\langle i_{\text{sig-sp}}^2\rangle$, the spontaneous–spontaneous emission beat noise generated within each amplifier ($\langle i_{\text{sp-sp},i}^2\rangle$, $i=1,2$), and the amplified spontaneous emission beat noise of the first amplifier by the second amplifier ($\langle i_{\text{sp-sp},12}^2\rangle$) are given respectively as follows:

$$\langle i_{\text{shot}}^2\rangle = 2e^2\eta_D\left(\frac{P_{la}}{E}C_1^2C_2^2\prod_{i=1}^{2}L_iG_i\right)\cdot L_3 + 2e^2\eta_D \cdot\sum_{i=1}^{2}\left\{(G_i-1)n_{sp}m_t\Delta f_1C_2L_3\prod_{j=i+1}^{2}(L_jC_1G_jC_2)\right\} \tag{7}$$

$$\langle i_{\text{sig-sp}}^2\rangle = 2e^2\eta_D^2\Big[G_1(G_1-1)F_o\frac{P_{la}}{E}L_1C_1C_2^2\cdot(L_2C_1G_2C_2L_3)^2 + G_2(G_2-1)\cdot F_oL_2L_1G_1C_1^2C_2^3\frac{P_{la}}{E}\cdot L_3^2\Big] \tag{8}$$

$$\langle i_{\text{sp-sp},1}^2\rangle + \langle i_{\text{sp-sp},2}^2\rangle = 2e^2\eta_D^2\big[(G_1-1)^2n_{sp}^2\cdot m_t\Delta f_2\cdot C_2^2\cdot\cdot(L_2C_1G_2C_2L_3)^2 \tag{9}$$
$$+ (G_2-1)^2n_{sp}^2m_t\cdot\Delta f_2\cdot C_2^2\cdot L_3^2\big] \tag{10}$$

$$\langle i_{\text{sp-sp},12}\rangle = 2e^2\eta_D^2\big[G_2(G_2-1)F_oL_2(G_1-1)C_2n_{sp}m_t\cdot\Delta f_1\cdot C_1\cdot C_2^2L_3^2\big] \tag{11}$$

where $F_o = 2n_{sp}\chi$ is the noise figure of the TWLA.

TABLE I
Definitions of Mathematical Symbols

$\langle n_1\rangle$, σ_1^2	Mean and variance of photon no./second at the first TWLA output (into fiber)
$\langle n_2\rangle$, σ_2^2	Mean and variance of photon no./second at the second TWLA output (into fiber)
$\langle n_3\rangle$, σ_3^2	Mean and variance of photon no./second before the photodetector
P_{la}	Laser mean launched optical power (into fiber)
L_1	Fiber and/or splitter loss between the laser and the first amplifier
L_2	Fiber and/or splitter loss between the first and second amplifiers
L_3	Fiber and/or splitter loss between the second amplifier and the detector
C_1, C_2	Coupling losses of the front and back facets of the TW amplifiers, respectively
G_1, G_2	The internal gains of the two TW amplifiers, respectively
$\sigma_{i,\text{sig-sp}}^2$ ($i=1,2$)	Signal–spontaneous beat terms of σ_i^2 (the third term in eq. (4) and (5), respectively)
$\sigma_{i,\text{sp-sp}}^2$ ($i=1,2$)	Spontaneous–spontaneous beat terms of σ_i^2 (the fourth term in eq. (4) and (5), respectively)
$\sigma_{2,\text{shot}}^2$	Shot noise terms of σ_2^2 (the first two terms in eq (5))
E	Photon energy ($h\nu$)
η_D	Product of the p-i-n diode quantum efficient and coupling efficiency between single-mode fiber and detector
n_{sp}	Population inversion parameter
χ	Excess noise coefficient
m_t	Effective number of transverse modes
Δf_1	Equivalent noise bandwidth for the spontaneous emission shot noise
Δf_2	Equivalent noise bandwidth for the beat noise between spontaneous emission components
k	Boltzmann constant
T	Absolute temperature in degrees kelvin
F_o	Noise figure of optical amplifier ($= 2n_{sp}\chi$)
m	Optical modulation index

B. Noise in N-Stage TWLA's

The above analysis can be generalized to the case of N-stage TWLA's; the results are summarized below:

$$\langle i_{\text{shot}}^2 \rangle = 2e^2\eta_D \frac{P_{\text{la}}}{E} \cdot L_{N+1} \cdot \prod_{i=1}^{N} L_i C_1 G_i C_2 + \sum_{i=1}^{N} \left\{ (G_i - 1) n_{\text{sp}} m_t \Delta f_1 \cdot C_2 \cdot L_{N+1} \prod_{j=i+1}^{N} (L_j C_1 G_j C_2) \right\} \quad (12)$$

$$\langle i_{\text{sig-sp}}^2 \rangle = 2e^2\eta_D^2 \frac{P_{\text{la}}}{E} \cdot F_o \cdot \sum_{i=1}^{N} \left\{ \left[\prod_{j=1}^{i} C_1 L_j G_j C_2 \right] \cdot C_2 \cdot (G_i - 1) \cdot L_{N+1}^2 \cdot \prod_{j=i+1}^{N} (L_j C_1 G_j C_2)^2 \right\} \quad (13)$$

$$\sum_{i=1}^{N} \langle i_{\text{sp-sp},i}^2 \rangle = 2e^2\eta_D^2 \cdot \sum_{i=1}^{N} \left\{ (G_i - 1)^2 \cdot n_{\text{sp}}^2 \cdot m_t \cdot \Delta f_2 \cdot C_2^2 L_{N+1}^2 \cdot \prod_{j=i+1}^{N} (L_j C_1 G_j C_2)^2 \right\} \quad (14)$$

$$\sum_{j>i}^{N} \langle i_{\text{sp-sp},ij}^2 \rangle = 2e^2\eta_D^2 \cdot F_o \cdot \sum_{i=1}^{N-1} (G_i - 1) \cdot C_2 \cdot n_{\text{sp}} m_t \Delta f_1 \cdot \left\{ \sum_{j>i}^{N} \left[C_2 \prod_{p=i+1}^{j} (L_p C_1 G_p C_2)(G_j - 1) \cdot \left(L_{N+1}^2 \cdot \prod_{m=j+1}^{N} (L_m C_1 G_m C_2)^2 \right) \right] \right\}. \quad (15)$$

To simplify calculations, we further define two new parameters by assuming $G_1 = G_2 = \cdots = G$:

$$\langle i_{\text{sp-sp,self}}^2 \rangle = 2e^2\eta_D^2 \cdot (G-1)^2 \cdot n_{\text{sp}}^2 m_t \Delta f_2 C_2^2 \quad (16)$$

$$\langle i_{\text{sp-sp,cross}}^2 \rangle = 2e^2\eta_D^2 \cdot (G-1)^2 \cdot n_{\text{sp}}^2 \chi m_t \Delta f_1 C_2^2. \quad (17)$$

These two parameters have about the same value for $\chi = 1$ and $\Delta f_1 \approx \Delta f_2$. Note that $\langle i_{\text{sp-sp,self}}^2 \rangle$ is a measurable quantity from a single TWLA. Therefore (14) and (15) can be rewritten respectively as

$$\sum_{i=1}^{N} \langle i_{\text{sp-sp},i}^2 \rangle = \langle i_{\text{sp-sp,self}}^2 \rangle L_{N+1}^2 \sum_{i=1}^{N} \prod_{j=i+1}^{N} (L_j C_1 G_j C_2)^2 \quad (18)$$

$$\sum_{j>i}^{N} \langle i_{\text{sp-sp},ij}^2 \rangle = 2\langle i_{\text{sp-sp,cross}}^2 \rangle \cdot \sum_{i=1}^{N-1} \cdot \left\{ \sum_{j>i}^{N} \left[\prod_{p=i+1}^{j} (L_p C_1 G_p C_2) \cdot \left(L_{N+1}^2 \cdot \prod_{m=j+1}^{N} (L_m C_1 G_m C_2)^2 \right) \right] \right\}. \quad (19)$$

The expressions for signal–spontaneous and spontaneous–spontaneous emission beat noise can be further simplified by assuming the following conditions: 1) all TWLA's are identical and have the same coupling efficiencies on both facets; 2) all intermediate transmission losses or coupling losses are identical ($L_1 = L_2 = \cdots = L_N = L$); and 3) fiber-to-fiber gain of a TWLA compensates the fiber transmission and splitting loss, i.e., $C_1 G C_2 = L^{-1}$. We then obtain

$$\langle i_{\text{sig-sp}}^2 \rangle = N \cdot 2e^2\eta_D^2 \cdot \frac{P_{\text{la}}}{E} \cdot F_o \cdot C_2 (G-1) \cdot L_{N+1}^2 \quad (20)$$

and the current spectral density of the dominant spontaneous–spontaneous emission beat noise can be obtained from (19) as (the term given by (18) is negligible compared to (19) when N is large)

$$\sum_{j>i}^{N} \langle i_{\text{sp-sp},ij}^2 \rangle = N \cdot (N-1) \cdot \langle i_{\text{sp-sp,cross}}^2 \rangle \cdot L_{N+1}^2. \quad (21)$$

Note that the spontaneous–spontaneous emission beat noise is proportional to the number of stages in terms of N^2 (obtained from eq. (18) + eq. (21)), which increases much faster than the signal–spontaneous beat noise. We assume that the spontaneous–spontaneous emission beat noise could be eliminated by using narrow-band optical filters between amplifier stages. So the CNR per unit bandwidth due to signal–spontaneous beat noise alone can be written as

$$(\text{CNR})^{-1} = \frac{\langle i_{\text{sig-sp}}^2 \rangle}{\frac{1}{2} \cdot m^2 \cdot \left(\frac{P_{\text{la}}}{E} e\eta_D L_{N+1} \right)^2} \approx N \cdot \frac{4E \cdot F_o}{m^2 C_1 \cdot P_{\text{in}}} \quad (22a)$$

$$= N \cdot \frac{4e\eta_D F_o}{m^2 C_1 \cdot I_D \cdot \frac{L}{L_{N+1}}} \quad (22b)$$

where m is the optical modulation index per video channel (OMI/channel) and P_{in} is the mean signal power at the input of each amplifier. Equation (22b) is easier to use than (22a) if one knows the received signal photocurrent I_D (excluding the amplified spontaneous emission noise).

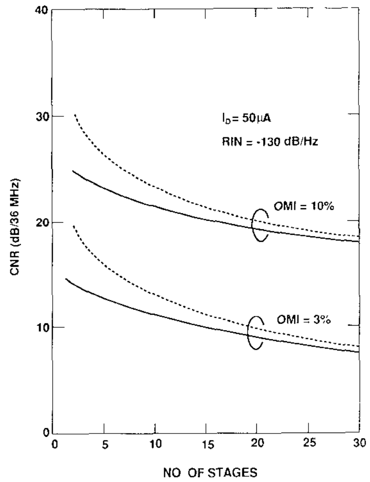


Fig. 5. CNR per FM-TV channel versus number of cascaded TWLA's for two values of optical modulation index (OMI). The dotted lines consider only the signal–spontaneous beat noise, and the solid lines consider all noise terms. It is assumed that the fiber-to-fiber gain of each TWLA compensates the coupling and transmission losses between two TWLA's. The receiver's equivalent input noise current spectral density is assumed to be 6.4×10^{-22} A^2/Hz. $C_1 = 5$ dB, $G = 20$ dB, $F_o = 6$ dB, $\eta_D = 0.8$.

C. Overall System CNR

From the analysis given in subsections A and B, the CNR per unit bandwidth of each received video signal after transmission through N-stage TWLA's can be written as

$$\mathrm{CNR}^{-1} = \frac{2\cdot \mathrm{RIN}}{m^2} + \frac{2\langle i_{\mathrm{ckt}}^2\rangle}{m^2\cdot I_D^2} + \frac{4e}{m^2\cdot I_D} + \frac{2\langle i_{\mathrm{OA}}^2\rangle}{m^2 I_D^2} \tag{23}$$

where

$$\langle i_{\mathrm{OA}}^2\rangle = \langle i_{\mathrm{sig-sp}}^2\rangle + N\cdot\langle i_{\mathrm{sp-sp},i}^2\rangle + \sum_{j>i}^{N}\langle i_{\mathrm{sp-sp},ij}^2\rangle, \qquad i,j = 1,2,\cdots,N \tag{24}$$

and $\langle i_{\mathrm{ckt}}^2\rangle$ is the receiver's equivalent input noise current spectral density. In most cases, the spontaneous–spontaneous beat noise can be eliminated by using optical filters; hence by considering (22b), we can simplify (23) as

$$\mathrm{CNR}^{-1} = \frac{2\cdot \mathrm{RIN}}{m^2} + \frac{2\langle i_{\mathrm{ckt}}^2\rangle}{m^2\cdot I_D^2} + \frac{4e}{m^2\cdot I_D} + N\cdot\frac{4e\eta_D F_o}{m^2 I_D C_1\cdot\dfrac{L}{L_{N+1}}}. \tag{25}$$

Using (25) and assuming $L_{N+1} = L$, we have derived the CNR as a function of the number of cascaded TWLA's for the case of transmitting multichannel FM video signals, as shown in Fig. 5. We notice that at the first few stages, the dominant noise at a detected photocurrent of 50 μA is the postdetector preamplifier thermal noise; as the number of stages increases, the dominant noise becomes the signal–spontaneous beat noise. Increasing the OMI/channel can significantly improve the system CNR performance, as indicated in (22) and shown in Fig. 5. If the OMI/channel is only 3%, than only about two stages of TWLA's can be used in order to obtain video signals with near studio quality, which was verified in our experiment (see subsections IV-B and IV-C). However, if the OMI/channel is increased to 10% (by decreasing the number of video signals, for example) while keeping the IMD noise 20 dB below the fundamental carriers, more than 30 TWLA's can be cascaded with studio quality video signals received. Also, from (22), we see that a better SNR can be obtained if the front facet coupling efficiency C_1 of the TWLA's can be increased and if the noise figure of the optical amplifiers can be reduced.

IV. Multichannel FM-Video System Experiments

In this section, we will present experimental results on a) a 10-FM video SCM system employing a single-stage TWLA and b) a 90-FM video SCM system employing two cascaded TWLA's. Calculated system CNR (according to Section III) is given to explain the effect of various noise terms in such systems.

A. Single-Stage TWLA—10 FM-TVs

A composite of ten FM video signals from a C-band satellite (ranging from 3.7 to 4.2 GHz, with a bandwidth of 36 MHz per channel) was used to intensity modulate a 1298 nm GaInAsP Fabry–Perot (FP) laser (with FWHM of about 2 nm) with a 3 dB bandwidth of 6 GHz. After passing through an input attenuator and a polarization controller, the modulated light was amplified by a TWLA, and detected by a high-speed InGaAs p-i-n diode. No optical isolator was used.

1) CNR Performance: The CNR of a FM video signal was measured as a function of the total attenuation by adjusting the output attenuator, both with and without the TWLA. Input power levels at −15 and −22 dBm to the TWLA were tested, respectively. Only a slight decrease of the CNR (about 1 dB) was observed due to signal–spontaneous beat noise when the input power was −15 dBm. This degradation is more pronounced when the input optical power is decreased to −22 dBm.

To examine the various noise contributions in the present system, a set of measured data showing the CNR versus input attenuation (by adjusting the input attenuator while keeping the output attenuator at 3 dB) is shown in Fig. 6. Solid lines are the calculated results. We observe from Fig. 6 that the dominant noise term at high received optical power is the effective relative intensity noise ($\mathrm{RIN_{eff}} = -119$ dB/Hz, which includes the intermodulation noise in the system and the incoming satellite signal background noise) and the low-noise-amplifier (LNA) thermal noise dominates at the lower received optical power. Owing to the low sensitivity (−20 to −13 dBm) of a receiver with a 50 Ω input impedance in an SCM system, the signal–spontaneous beat noise, spontaneous–spontaneous emission beat noise, and shot noise have negligible effect (compared to the LNA thermal noise) on the system CNR performance.

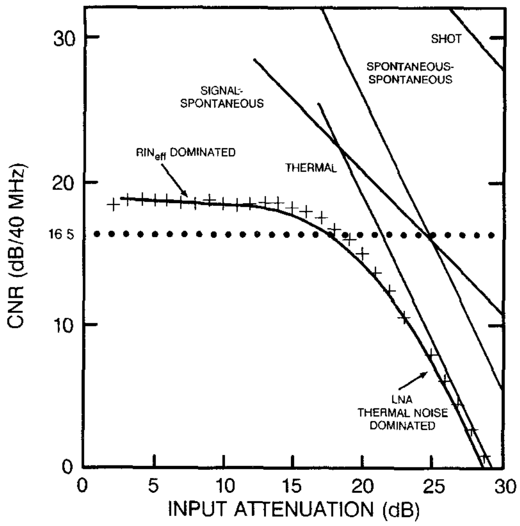


Fig. 6. (Single-stage TWLA) CNR against input attenuation loss with output attenuation at 3 dB. Solid lines are calculated data and crosses are measured data. Calculated contributions from various noise terms are also plotted. Parameters used for calculation are: $m = 0.09$, $RIN_{eff} = -119$ dB/Hz, $\langle i_{ckt}^2 \rangle = 4.0 \times 10^{-22}$ A^2/Hz, $F_o = 6$ dB, $\langle i_{spsp}^2 \rangle = 10^{-22}$ A^2/Hz, $C_1 = C_2 = 5$ dB, $G = 20$ dB, $\eta_D = 0.4$.

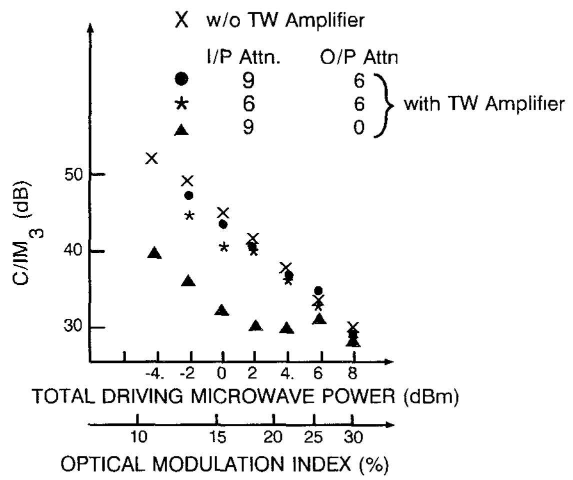


Fig. 7. Power ratio of fundamental carrier to third-order intermodulation products (C/IM_3) against optical modulation index (two tones are 3.93 and 3.97 GHz).

2) Microwave Nonlinear Distortions: Two microwave tones (3.93 and 3.97 GHz) were used to drive the laser and examine the resulting third-order intermodulation distortion (IMD), both with and without the TWLA. The results are shown in Fig. 7. By varying the input and output attenuators, it was observed that the increase in IMD was mainly due to the backward-propagating amplified optical reflection from the p-i-n diode into the laser (note there was no optical isolator used in this particular experiment). When the laser was driven by two stronger microwave tones, the IMD remained essentially unchanged with or without TWLA, because the laser became less sensitive to far-end reflections due to reduction in the laser coherence length under strong modulation.

We found that if the laser was driven strongly to increase the OMI, the dominant noise terms are from the IMD at higher received optical power and LNA thermal noise at lower received optical power. This shows the merits of an FM video system using a TWLA, since a multichannel FM system can tolerate significant IMD (provided it is about 20 dB below the fundamental carriers) and is therefore relatively immune to the TWLA noise. For the two tones around 4 GHz range with 40 MHz separation, the IMD level remains essentially unchanged with or without the traveling-wave laser amplifier, provided that the OMI is reasonably large or the backward-propagating amplified optical reflection can be properly attenuated, both to reduce the effect of coherent optical feedback on the laser linearity.

We have also examined the IMDs by using two tones at 1.8 and 1.84 GHz, with an optical power of −2.75 dBm into the TWLA and OMI = 11.75%/channel (the TWLA gain was operated 2 dB into saturation). The resulting third- and second-order IMD's were 42 dB and 49 dB below the fundamental carriers, respectively; for two tones at 1.2 and 1.24 GHz, the resulting third- and second-order IMD's were 51 and 45 dB below the fundamental carriers (the higher third-order IMD's at higher microwave frequencies were mainly due to their proximity to laser relaxation oscillation frequency; on the other hand, the higher second-order IMD's at lower frequencies were due to the carrier density modulation by the beat frequencies). The low level nonlinear IMD's from these measurements suggest that, for the transmission of multichannel microwave FM video signals, the nonlinear IMD's due to a TWLA (induced by signal-dependent carrier density modulation) will not affect a received FM-TV CNR. The effect of carrier-density-modulation-induced IMD's becomes more significant for the case of multichannel AM-VSB TV systems where the carrier frequencies are below several hundred megahertz, as will be examined more carefully in Section V.

B. Two-Stage TWLA's – 90 FM-TVs

The experimental setup for a two-stage TWLA experiment is shown in Fig. 8. The 90 FM video signals were derived from the *C*-band satellite signal described in subsection III-A. The *C*-band signal was up- and down-converted and frequency multiplexed into nine frequency bands by using two mixers and two local oscillators. The resulting 90-channel signal ranged from 1.7 to 6.2 GHz. The InGaAsP laser used had a bandwidth of 7 GHz at a power level of 8 mW. At the receiving end, a p-i-n diode with a bandwidth of 10 GHz and a responsivity of 0.84 A/W and a 2–8 GHz amplifier with 30 dB gain and a noise figure of 3 dB were employed.

The CNR of a received *C*-band video signal was measured with respect to the total transmission loss, as shown in Fig. 9. The solid lines in Fig. 9 are the calculated results using (7)–(11) and (23) for $N = 2$, together with the parameter values listed in the figure caption. At a CNR of about 15 dB (which corresponds to a SNR of about 54.5 dB [10]), the system power margin was increased by 20 dB due to the two cascaded amplifiers. The CNR degradations are

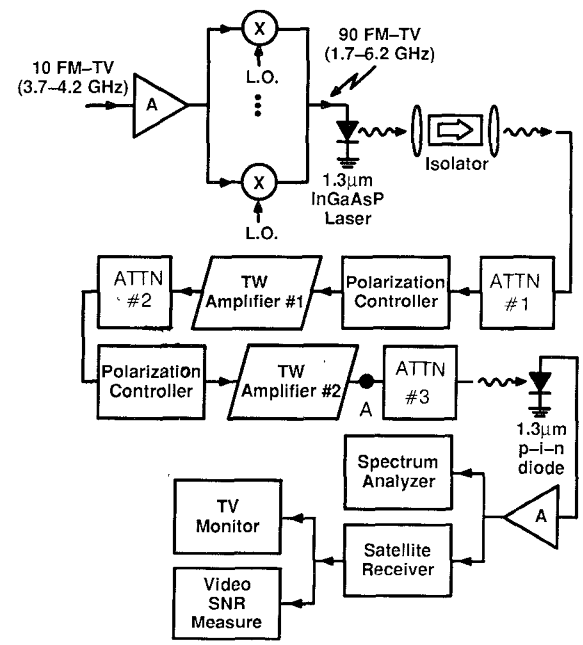


Fig. 8. Experimental setup for transmission of 90 FM-TVs through a high-speed laser amplifier and two cascaded TWLA's.

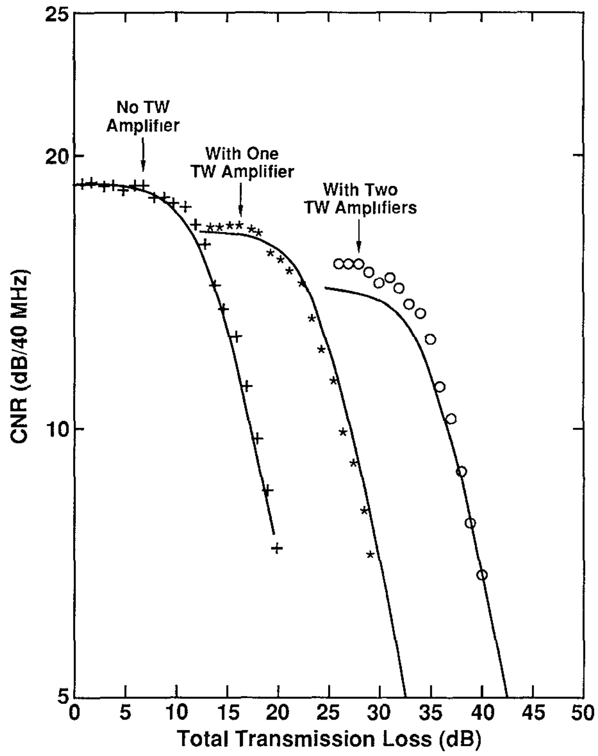


Fig. 9. 90 FM-TVs, two TWLA's experiment: CNR versus total attenuation loss. Solid lines are the calculated results based on the following parameter values: $m = 0.03$, $RIN_{eff} = -128.5$ dB/Hz, $\langle i^2_{ckt} \rangle = 6.4 \times 10^{-22}$ A^2/Hz, $F_o = 6$ dB, $\langle i^2_{spsp} \rangle = 10^{-22}$ A^2/Hz, $C_1 = C_2 = 5$ dB, $G = 20$ dB, $\eta_D = 0.7$

attributed to the signal–spontaneous beat noise of the cascaded amplifiers, and the low OMI used in the 90-channel system. Like the results of subsection IV-A, the CNR degradations caused by spontaneous–spontaneous emission beat noise and the shot noise from the amplified spontaneous emission noise (-8 dBm measured after the second TWLA at point A in Fig. 8) were found to be negligible.

To study the various noise contributions in the present system, the CNR versus attenuation #2 (with attenuation #1 fixed at 9.5 dB and attenuation #3 at 6 dB) is plotted in Fig. 10. The solid lines are the calculated results. We observe from Fig. 10 that the dominant noise sources are the effective intensity noise RIN_{eff} of the system (including the LD nonlinear IMD's and incoming satellite signal background noise) at high received optical power and the preamplifier thermal noise at low received optical power. In the region where attenuation #2 is between 16 and 20 dB, the CNR exhibits a L^{-1} variation, which is mainly caused by the signal–spontaneous beat noise. The spontaneous–spontaneous emission beat noise is negligible because the SCM system was operated at a high optical power level. From Fig. 10, we observe that the optimum attenuation between the two TWLA's, when both are used as in-line amplifiers, is about 14 dB when attenuation #1 is 9.5 dB.

The received baseband signals of the 90 video signals have SNR's ranging from 52 to 56 dB at an OMI of 3% per channel and at a received optical power of -14 dBm.

In Fig. 9, the pronounced CNR degradations after two cascaded TWLA's are due to (a) low OMI/channel (only 3% per channel for the 90-channel system, compared to 9% per channel for the 10-channel system) and (b) the fact that signal–spontaneous beat noise increases linearly with

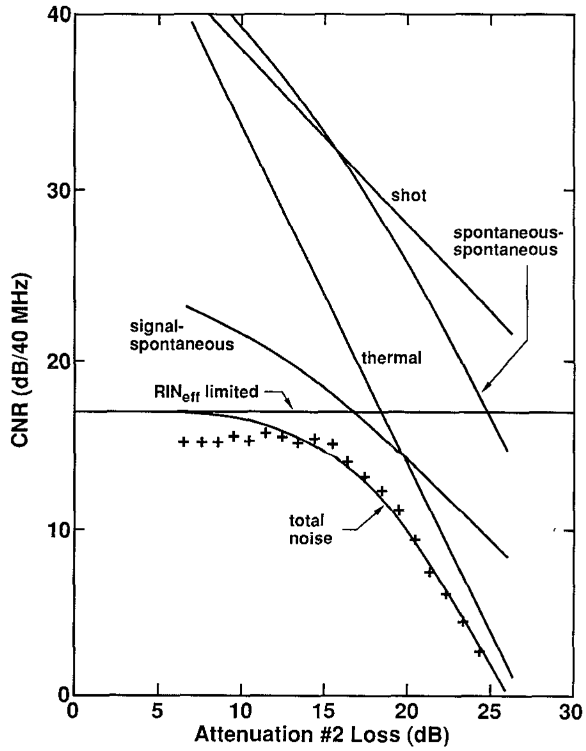


Fig. 10. Two cascaded in-line TWLA's: CNR versus attenuation #2. Attenuation #1 = 9.5 dB, attenuation #2 = 6 dB (including connector losses). Solid lines are calculated results.

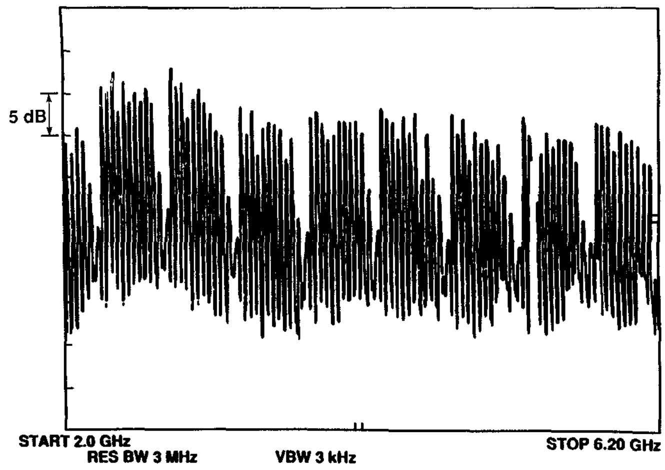


Fig. 11 Microwave spectrum showing the received multiple channels of FM-TVs after two in-line TWLA's and 2048 splits. Signals between 1.7 and 2 GHz were not shown

the number of cascaded TWLA's, as has been discussed in subsection III-B.

Considering the signal–spontaneous beat noise contribution in Fig. 10, we observe a noticeable bend of the CNR performance when attenuation #2 is smaller than about 15 dB. No similar bend is observed in Fig. 6 for a single-stage TWLA. This tells us that there should be enough loss between TWLA's to avoid CNR degradations due to the beat noise between the signal and the amplified spontaneous emission from previous stages.

C. Distribution of 90-Channel FMTV to 2048 Subscribers

The 20 dB gain obtained from the two cascaded amplifiers (subsection IV-B) can be utilized to increase the span length in the point-to-point system or, more importantly, for power splitting in a point-to-multipoint distribution system. We investigated the latter application in a feasibility demonstration to distributing 90 FM television channels to 2048 terminals. The first optical attenuator (attn #1) in Fig. 8 was replaced by several stages of optical couplers resulting in 1×16 split; the second optical attenuator (attn #2) in Fig. 8 was replaced by a 1×16 optical splitter; the third optical attenuator (attn #3) in Fig. 8 was replaced by a 1×8 splitter. The number of terminals that can receive the 90-channel signal is thus 2048. The RF spectrum (2–6.2 GHz) of the received 90-channel signal is shown in Fig. 11, where each spike represents an FM video channel. The baseband SNR was measured by a C-band satellite receiver and automatic SNR measurement equipment. Provided the OMI/channel was 3.5%, the received baseband SNR could reach the broadcast quality requirement of 56 dB. The CNR's in the last band of ten channels (i.e., from 5.7 to 6.2 GHz) were generally lower than the C-band channels by about 4 dB because of the roll-off of the laser and the 2–8 GHz postdetector amplifier. The CNR's of the channels in the first band (i.e., from 1.7 to 2.2 GHz) were about 3 dB lower than the C-band channels. The 39.5 dB difference between CNR and SNR indicates that the channels in the first and last bands had SNR's of 53 and 52 dB, respectively. The SNR's thus obtained in all channels reached well above the minimum cable TV SNR requirement of 43–45 dB.

TABLE II
POWER BUDGET FOR THE EXPERIMENT

Laser power launched into single-mode fiber	+ 1.4 dBm
Gain of traveling-wave laser amplifiers (fiber-to-fiber, include one connector pair each)	+ 12 X 2 dB
Power splitter loss (all include one biconic connector pair):	
1 X 2	- 3.6 dB
1 X 2	- 4.0 dB
1 X 4	- 6.1 dB
1 X 16	-13.0 dB
1 X 8	- 9.5 dB
Polarization controller loss (all include one biconic connector pair):	
#1	- 1.0 dB
#2	- 0.5 dB
Jumpers and 3 connector pairs:	- 2.0 dB
Power received by the p-i-n diode	-14.3 dBm

The system power budget is listed in Table II. Note that we have increased the gain of each TWLA to 12 dB, and altogether there are 12 in-line biconic connectors used in the present distribution system. The total system power margin is 39.7 dB.

V. MULTICHANNEL AM-VSB VIDEO SYSTEM EXPERIMENT

Multichannel AM-VSB television signals have been transported by using a laser diode [11], [12]. However, as opposed to a lightwave system transporting multi-channel FM-TVs, the CNR requirement on each individual channel is much higher (a minimum of 43–45 dB), this in turn severely limits the system power margin to 5–10 dB. Doped-fiber amplifier has been used to transport multichannel AM-VSB signals [13]. TWLA's were originally thought not to be suitable for VHF AM-VSB television signal transmission [14], because of the signal-induced carrier density modulation which causes significant IMD's. Our measured results show that second-order IMD's are very high, however, third-order IMD's are much lower than second-order IMD's. Accordingly, a system experiment was carried out by keeping all the AM-VSB channels within an octave of frequency range.

A highly linear laser diode with 1.307 μm wavelength and a threshold current (I_{th}) of 21 mA was used. The linearity of the laser diode was first characterized by using two-tone measurement. At a bias level of $2.2 \cdot I_{th}$, and an OMI of 24% per channel (total OMI 34.9%), the second- and third-order IMD's were 60 dB and 65 dB below the fundamental carriers, respectively. The modulated laser light passed through an optical isolator, a variable optical attenuator, a polarization controller and then to a TWLA. The polarization controller was used to minimize the nonlinear distortion products [15].

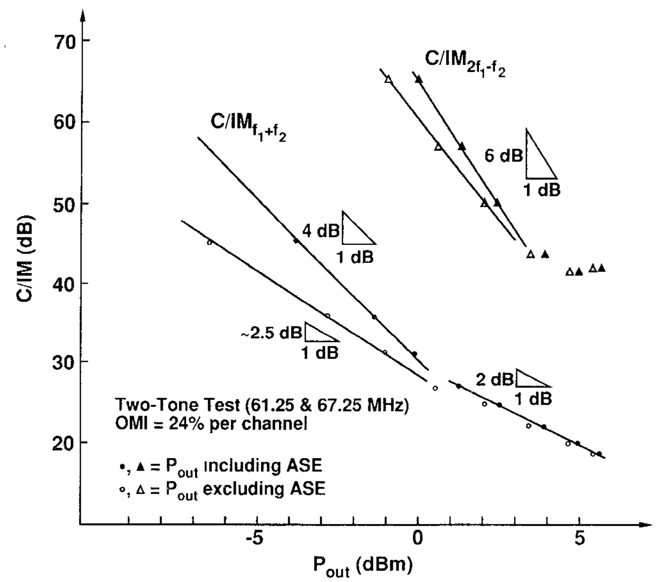


Fig. 12. Electrical power ratio of carrier to intermodulation and harmonic distortions versus the optical output power from the TWLA. Two RF tones were at 61.25 and 67.25 MHz, respectively. The data were obtained from varying the input power to the TWLA.

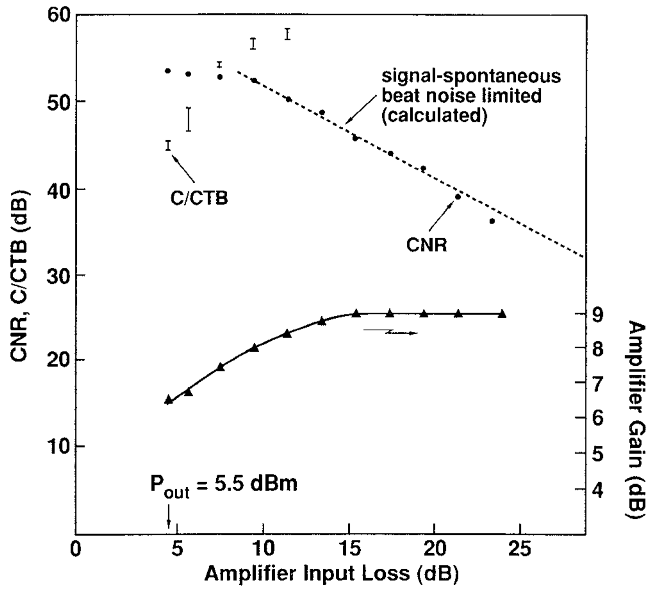


Fig. 13. Carrier-to-noise ratio (CNR) and carrier-to-composite-triple-beat ratio (C/CTB) versus the TWLA input loss, for the 12-channel transmission. The measured parameters used for the calculation of signal-spontaneous noise limited CNR are as follows: $m = 11\%$ per channel, $C_1 = 5$ dB, $P_{1a} = 5$ dBm, $\eta_D = 0.85$, $F_o = 6$ dB, RIN $= -142$ dB/Hz.

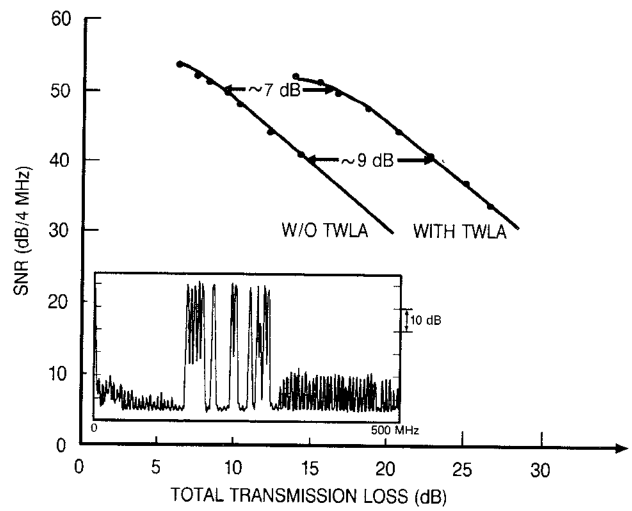


Fig. 14. CNR per channel versus total transmission loss, without and with a TWLA.

Fig. 12 shows the measured ratios of carrier-to-second-order intermodulation (C/IM$_{f_1+f_2}$), and carrier-to-third-order intermodulation (C/IM$_{2f_1-f_2}$) as functions of the TWLA output power (P_{out}). Two sets of data are shown, one with P_{out} including the amplified spontaneous emission noise (ASE), and the other with P_{out} excluding the ASE. The data were obtained by changing the optical input power to the TWLA. For P_{out} lower than about 0 dBm, the measured C/IM$_{f_1+f_2}$ decreased 4 dB for every dB increase in P_{out} which included ASE, and C/IM$_{f_1+f_2}$ decreased about 2.5 dB for every dB increase in P_{out} which excluded ASE. When the amplifier output power exceeded the 3-dB gain-saturated power (+3 dBm into single-mode fiber), C/IM$_{f_1+f_2}$ decreased 2 dB for every dB increase in P_{out} (both for the cases of including and excluding ASE). The C/IM$_{2f_1-f_2}$, on the other hand, was substantially higher. It remained at a level of about 65 dB until P_{out} approached the 3 dB gain saturation power. However, when P_{out} was in excess of 0 dBm, it dropped at a rapid rate of about 6 and 4 dB for every dB increase in P_{out} including ASE, and P_{out} excluding ASE, respectively. When P_{out} exceeded +3 dBm, a saturated level of C/IM$_{2f_1-f_2}$ was observed to be around 41–42 dB, most likely due to the amplifier limiting effect.

According to the measured results in Fig. 12, it is possible to transport multi-channel AM-VSB television signals provided the signal frequencies can be kept within one octave to avoid high second-order nonlinear distortions, and provided the TWLA can be operated in the linear gain region. In our system experiment, 11 channels of voltage-controlled oscillators and one actual video channel (all between 150 and 300 MHz) were combined to intensity modulate the DFB laser. The OMI per video channel was about 11%. The laser output power was around 5 dBm. The measured CNR per channel, and the worst carrier-to-composite triple beat (C/CTB), versus the amplifier input loss (which did not include the coupling loss), are shown in Fig. 13. The attenuation between the TWLA and the photodetector was adjusted so that the photodetector was operated in the linear region. The amplifier gain saturation characteristics, and a calculated signal-spontaneous beat noise limited CNR (from eq. (22a)), are also shown in the same figure. At an input loss of about 10 dB, the amplifier gain was saturated by 1 dB, and the C/CTB was decreased from > 60 dB (in the linear region) to about 56 dB; on the other hand, at an input loss of more than 12 dB, the signal–spontaneous noise began to become a limiting factor. If a subscriber loop distribution system requires CNR ⩾ 45 dB, C/CTB ⩾ 55 dB, the optimum amplifier input loss is then between 10 and 16 dB. The result implies that the TWLA can only be used as an in-line- or preamplifier, but not as a power amplifier, for the transmission of multichannel AM-VSB video signals. A higher 3 dB output saturation power than the current case (+3 dBm into single-mode fiber) is preferred for the application of a TWLA as an in-line amplifier. The SNR ($\approx$ CNR) per channel versus the total transmission loss is shown in Fig. 14. The TWLA input loss was fixed at 10 dB, and the output loss was varied to obtain the data. We can see that a net system gain of 7 and 9 dB was obtained at a CNR of 50 and 40 dB, respectively. The RF spectrum of the received AM-VSB video signals at an amplified output power of 0 dBm is shown in the inset of Fig. 14. Fairly high second-order nonlinear distortions due to the semiconductor amplifier can be observed, while the inband third-order nonlinear distortions were all lower than the fundamental carriers by about 55 dB.

VI. System Optical Reflection Considerations

The effect of TWLA's on optical reflections, is briefly discussed in this section. High optical reflectivities due to single-mode fiber connectors can effectively form an external pair of mirrors for a TWLA, and can significantly increase the gain ripple of the laser amplifier. These high optical connector reflectivities in turn will make the amplifier start to oscillate and become a laser. System performance will thus be severely degraded. Since a TWLA, in general, requires low reflectivity ($\leqslant 10^{-3}$) coatings on ordinary laser facets to prevent Fabry–Perot resonance, the return loss of a connector joint should be higher than 25 dB (assuming the coupling loss into and out of an amplifier to be 5 dB). This requirement can be alleviated if there is attenuation between the connector joint and the laser amplifier. As mentioned in subsection IV-C, 12 biconic connectors with an average reflectance of -30 dB were used. Therefore, for multichannel microwave FM-TV systems, connectors of -30 dB reflectances are acceptable. The other effect of optical reflections, as described in subsection IV-A, is the amplified backward-propagating feedback into the laser transmitter, which can cause corresponding degradations of laser linearity and intensity noise performance; therefore the use of an optical isolator is preferred.

The requirement on the connector reflectances, however, is much more stringent in the multichannel AM-VSB television lightwave system, mainly because of the multiple-reflection-induced interferometric noise [10], [16]. The interferometric noise usually is high in the frequency range below several hundred megahertz, and is therefore detrimental to VHF AM-VSB video signals. The connectors used in Section V had reflectances lower than -40 dB, with a mean of -45 dB, which were able to greatly reduce the effect of interferometric noise.

VII. Conclusion

We have investigated, both experimentally and analytically, the feasibility of distributing both multiple FM and AM-VSB video signals to end users by using TWLA's to increase the power margin of an SCM lightwave system. The major noise contribution from TWLA's is the signal–spontaneous beat noise, which becomes the dominant system noise when the number of cascaded TWLA's is large. If only a few stages of TWLA's are used and reasonable transmission loss is assumed, the dominant system noise is the thermal noise of the postdetector preamplifier with 50 Ω input impedance. The spontaneous–spontaneous emission beat noise of cascaded TWLA's increases as the square of the number of amplifier stages, which accumulates much faster than signal–spontaneous noise. Therefore, when cascading many TWLA's in an SCM system, it is necessary to use optical filters between the amplifier stages to eliminate spontaneous–spontaneous emission beat noise. However, in our multichannel FM-TV experiment when only two stages of TWLA's were cascaded, we did not see a need to use optical filters. Transmission loss between TWLA's should not be smaller than the TWLA fiber-to-fiber gain, in order to avoid CNR degradations due to the additional beat noise between the signal and the amplified spontaneous emission noise from previous stages, and to avoid amplifier gain saturation due to accumulated amplified spontaneous emission noise. The noise figure of a TWLA should be minimized, and the front facet coupling efficiency should be maximized, to improve the overall system SNR performance.

The signal-dependent carrier density modulation-induced IMD's due to a TWLA were found to have little effect on video CNR performance for multi-channel microwave FM-TV lightwave systems. However, it caused severe second-order IMD's in a system transporting multi-channel VHF AM-VSB video signals. Therefore, only video channels within an octave of frequency range could be delivered by a single laser diode in the latter case. Also, according to our measurements of microwave and RF nonlinear distortions (due to the carrier-density modulation in a TWLA) and various TWLA noise terms, we conclude that a TWLA can be used as a power, in-line, or preamplifiers for the transmission of multichannel FM video signals. On the other hand, a TWLA can only be used as either an in-line or a preamplifier for the transmission of multi-channel AM-VSB television signals. We demonstrated the in-line amplifier applications for both FM and AM signals: (1) by using two cascaded TWLA's, each one with 12 dB filter to fiber gain, 90 FM video signals were distributed to 2048 terminals, whereby each channel was received with near studio quality. The total system power margin was 39.7 dB; (2) 12-channel AM-VSB video signals between 150 and 300 MHz was transmitted with a total system power margin of 16 dB at a CNR of 50 dB/channel, and a composite triple beat 55 dB below carriers.

Besides increasing system power margin significantly, the TWLA's have an additional advantage that their costs can be shared by many end users. For the last stage TWLA, its cost can be shared by 8 (as in our experiment) to 30 (by increasing the TWLA gain and decreasing the connector losses) subscribers. This may be a more cost-effective alternative than installing high-sensitivity p-i-n-FET and APD receivers at each subscriber's site. Therefore, TWLA's are potentially good candidates for SCM subscriber loop video distribution systems. The implementation of TWLA's in a real-world environment, however, may encounter several practical limitations. For instance, residual reflectivities on a TW laser amplifier facets have to be small to avoid the gain ripples, and TE and TM optical confinement factors have be equal to achieve polarization-independent gain. Also, for a number of cascaded amplifiers, the effect of direct reflections and multiple reflections will impose a stringent requirement on the fiber connector/splice reflectivities.

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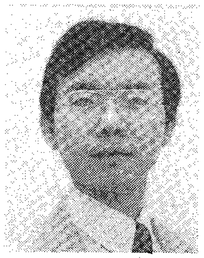
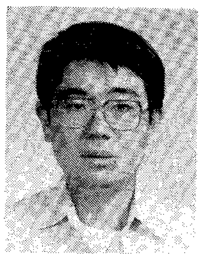


Winston Ingshih Way (S'82–M'82–SM'88) was born in Taiwan, Republic of China, in 1955. He received the B.S. degree from National Chiao-Tung University, Taiwan, in 1977, and the M.S.E.E. degree and the Ph.D. degree in electrical engineering and science from the University of Pennsylvania, Philadelphia, in 1981 and 1983, respectively.

From 1983 to 1984, he was an Assistant Professor at Temple University, Philadelphia, and a Consultant at the David Sarnoff Research Laboratory, RCA, Princeton, NJ. He has been with Bellcore since 1984 and has been involved in research on subcarrier multiplexed lightwave systems, including systems that distribute satellite, digital radio, and cable television signals. He has also worked on regenerator design for direct detection digital lightwave systems. His current interest is in the applications of semiconductor and doped-fiber optical amplifiers to the subscriber loop.

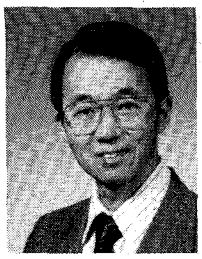


Chung-en Zah (S'83–M'85) was born in Taiwan, Republic of China, 1955. He received the B.S. and M.S. degrees from National Taiwan University, Republic of China, in 1977 and 1979, respectively, and the M.S. and Ph.D. degrees from the California Institute of Technology, Pasadena, in 1982 and 1986, respectively. All the degrees were in electrical engineering. His thesis research was in the area of millimeter-wave integrated circuits.

In 1985 he joined Bell Communications Research, Navesink Research Center, Red Bank, NJ. He is currently involved in research on optoelectronic devices for optical fiber communication systems including semiconductor lasers and optical amplifiers.

Dr. Zah is a member of the Optical Society of America.

Tien-Pei Lee (S'61–M'64–SM'77–F'84) was born in Nanking, China, in 1933. He received the B.S. degree in electrical engineering from National Taiwan University, Taiwan, China, in 1957; the M.S. degree from The Ohio State University, Columbus, in 1959; and the Ph.D. degree from Stanford University, Stanford, CA, in 1963.



He joined Bell Laboratories in Reading, PA, in 1963, where he was engaged in the development of microwave semiconductor devices. In 1966, he was transferred to the Guided Wave Research Laboratory at Crawford Hill, Bell Laboratories, Holmdel, NJ. From 1966 to 1968, he was involved in research on millimeter-wave repeater systems. Since 1968 his interest has been in fast optical detector diodes, semiconductor lasers, light emitting diodes, and optical fiber communication systems. Recently, his work has been in single-frequency and high-speed lasers for applications in the 1.0 to 1.6 μm wavelength region. Currently, he is District Manager, Photonic Device Research, Bell Communications Research, Red Bank, NJ. He has published over 140 technical papers and seven book chapters, and holds nine U.S. patents and five foreign patents on optical semiconductor devices.

Dr. Lee was the recipient of The Distinguished Technical Staff Award, Bell Laboratories (1983). He was an Associate Editor of the JOURNAL OF LIGHTWAVE TECHNOLOGY during the years 1986–1988. He is a member of Sigma Xi; the Chinese Institute of Engineers, U.S.A.; the Optical Society of America; and the American Association for the Advancement of Science.