Multi-Channel AM Fiber Optic CATV Trunks - From Lab to Reality

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ABSTRACT

In the past 12 months practical multi-channel AM fiber optic links have moved from the R&D lab into real world applications. In this paper, we focus on the design, characterization and performance capabilities of systems intended for use with signal spectra covering 20-80 CATV channels using distributed feedback (DFB) laser diodes and single mode optical fiber.

We discuss first the fundamental concepts used in a direct modulated AM laser based communications link. The noise and other degradation sources are identified and techniques used in mitigating their affects on performance are presented. Measurement techniques and practical results are also discussed.

We then discuss results on several laboratory demonstrations and field installations using the broad band AM link technology, with attention to the implementation issues faced by operators in the real-world environment of CATV networks.

1. INTRODUCTION

A year ago in Los Angeles, we heard several papers [1] on the architectural and technical aspects of fiber optic transmission for the CATV industry. Digital transmission, a combination of sophisticated Encoders, Decoders (CODECs), and off the shelf, mature, telephony-oriented transmission equipment, had been with us for many years. Frequency Modulation (FM) based systems were also available and being deployed in several markets. It was proposed, however, that neither Digital nor FM were on an appropriate cost-performance track to meet the most critical needs of the CATV operator - the trunking and distribution portions of the network. The solution? AM! (Amplitude Modulation).

Why AM? What was really being said was the following:

> "We know how to build high quality stacked VSB/AM signals in our head ends. The equipment is mature, cost effective, familiar and exists everywhere. We have set top converters and TV front ends in everybody's house, and they expect that stacked VSB/AM spectrum. And we can't afford to change everything at once, so whatever we add must be compatible on an incremental basis if we're to *evolve* to a fiber based network over a number of years."

Cost and available technology make AM an obvious choice for CATV fiber optic trunking. We have already observed that per-channel Digital and FM systems were applicable only to the high end part of the network (i.e., super trunking) and broadband interfaces for these techniques are not yet available. The challenge then for technologists is to solve the signal processing problem in the most direct manner - minimize the processing and maximize the performance of the transmission channel.

We at AT&T Bell Labs summarized these demands in the following set of design objectives:

1. The system must be cost effective.
2. The system must fit into existing architecture, yet be flexible enough to incorporate evolution.
3. The system must be compatible with the physical and environmental constraints of the typical CATV network.
4. The system must be installable and maintainable by the typical CATV technician.
5. The system must perform, now, and the technology must be capable of moving ahead with the advances in channel capacity, network size, and demands on performance anticipated for the future.

During 1988, several labs worked the issues that surfaced in LA and by year end, AM products were announced, delivered, installed, and put into service by several MSOs. Two basic architectures have emerged, one which recognizes the present limitations of off-the-shelf laser devices and uses several lasers in parallel to handle the spectrum, and a "home-run" single laser broadband architecture which demands premium performance from its components but delivers the simplest implementation.

In the following sections, we discuss the latter - a "home-run" architecture delivering 40 to 80 high quality CATV signals. Our focus is first on the technology issues, fundamental limitations and device characteristics, and finally on achieved performance.

2. A SIMPLE SYSTEM MODEL

A simple model of a fiber optic CATV trunk system is shown in Figure 1. The head end electronics here are modeled as N (N = # of channels) video modulators, converting a baseband video + audio signal to a VSB/AM signal at frequency f_n. The individual outputs are passively combined in several stages to form the composite spectrum.

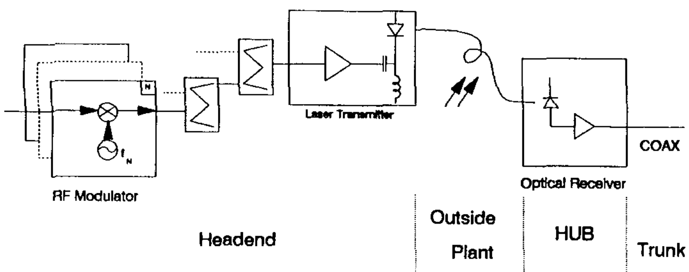


Figure 1

For our initial analysis, we will consider the performance with unmodulated carriers (CW case), resulting in frequency and time domain characteristics shown in Figures 2a and 2b, an analytical view of 42 cosinewaves summed together.

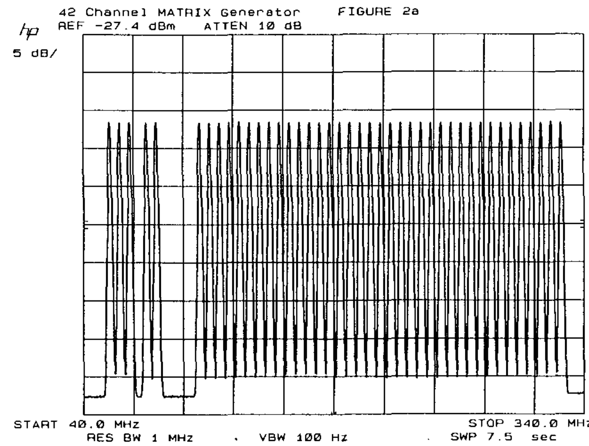
The laser transmitter is assumed to consist of an amplifier/driver device and a laser diode, at this level viewed as a current to light (optical) power converter. The laser launches this power into a single mode optical fiber, characterized by loss and dispersion (bandwidth), which delivers the power to a photo-detector diode at a remote location. The photo detector converts the incoming optical power to current, which is amplified and delivered to a load, here assumed to be a COAX cable distribution network.

3. A LOOK AT THE COMPONENT PARTS

3.1 Laser

The laser diode converts input current (modulation) to output light, a relationship often shown diagrammatically as in Figure 3a. This "L-I" characteristic shows several important parameters often considered when specifying lasers:

1. Threshold - The current level at which lasing (stimulated emission) begins.
2. Efficiency - The slope of the L-I characteristic, often referred to as dL/dI, in mw(opt)/ma.



Composite CATV VSB AM Signal

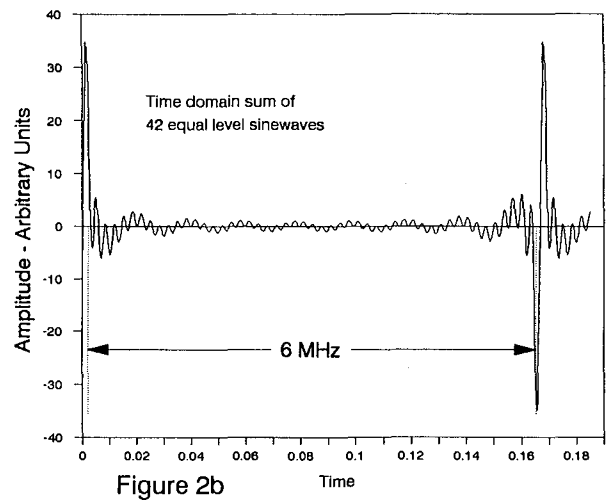


Figure 2b

3. Linearity - In general, you can only detect poor linearity from an L-I plot, not good linearity. A perfectly linear device follows a straight line over the region of operation, yet the deviation from "ideal" permissible for CATV applications is generally not measurable using L-I techniques.
4. Maximum Output - There is no simple definition of the maximum optical output from a laser device, rather it is a complex and device specific set of rules ultimately limiting the current density in the semiconductor junction. Most lasers exhibit a noticeable "rollover" or "current saturation" effect as shown in Figure 3a, where the non-linear L-I relationship becomes noticeable. For CATV applications, the maximum power is somewhat below this "observable" point on the L-I curve.

Not addressed on Figure 3 is the noise performance of the laser, normally specified as the *Relative Intensity Noise* (RIN). RIN is a significant contributor to overall AM link performance and will be discussed further below. As a device parameter, it is highly dependent on device structure and packaging.

Typical LASER L - I Curves

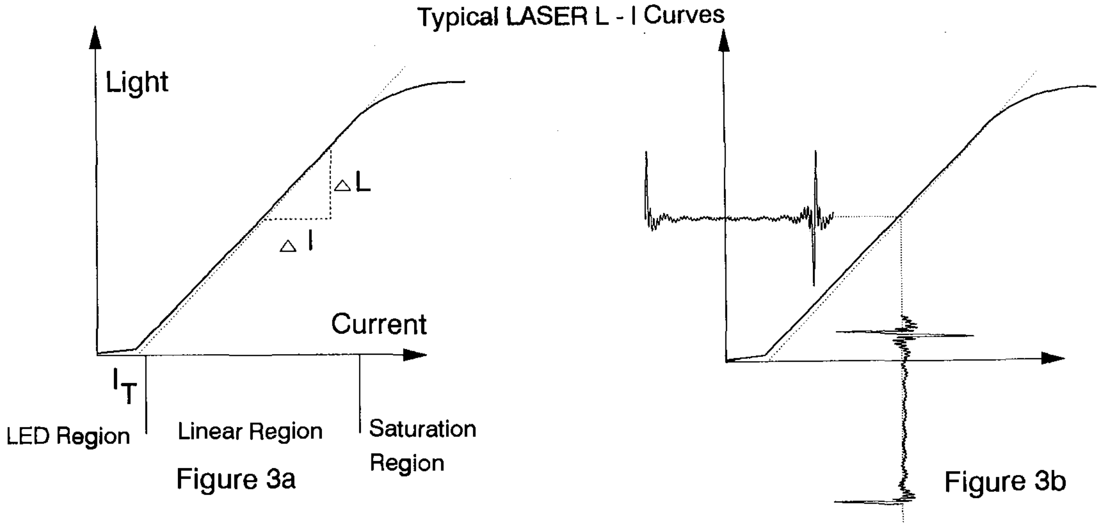


Figure 3a

Figure 3b

Intensity modulation, or modulating the amplitude of the optical oscillator (laser), is achieved by changing the current level in the device. Since we know our signal (time domain, Figure 2b), is symmetrical about zero mean (it is a sum of zero mean sine waves), a DC operating point for the laser will need to be established if the RF modulation is to see a uniform I $\rightarrow$ L conversion over its amplitude range, as depicted in Figure 3b.

3.2 Optical Isolator

A laser may be viewed as an oscillator whose amplitude and stability characteristics are strong functions of cavity (semiconductor material) purity, current stability, thermal stability, and input energy from intended and unintended sources. A significant source of unintended energy is a reflection somewhere in the output circuit which, due to (optical) impedance mismatch, couples energy from the load back into the oscillator at a random time, a function of the propagation time from the laser to the point of mismatch. As we will discuss later, we have determined that certain limits must be placed on the amount of reflected power that may return to the laser.

An isolator is a device that has very low insertion loss in one direction, high insertion loss in the other. These devices, mounted in or near the packaged laser, provide the necessary limiting of reflected power.

3.3 Fiber and Connectors

A detailed discussion of fiber and connector systems is beyond the scope of this paper. For our purposes, we need consider only the loss of the fiber and installed connectors (in dB) and, to some extent, the reflection performance of the complete optical circuit. In the context of this work, with lasers at $\lambda = 1.3\mu$ wavelength, the fiber dispersion is low enough to be insignificant, or in essence, the transmission medium is assumed to have infinite bandwidth.

3.4 Optical Detectors

Optical power transmitted through the fiber must be converted back to an electrical signal for input to the COAX cable network. Semiconductor diodes, typically *InGaAsP* or *Ge* at $\lambda = 1.3\mu$ wavelengths, are ideal for this application due to their small size, high bandwidth, high reliability, and low voltage operation. Two types of diodes are candidates; PINs and avalanche photo-diodes (APDs).

As we will see below, APDs are not applicable for high channel load applications since a significant portion of the noise in the system is present at the input to the detector in the form of laser noise and shot noise, both of which would be amplified by the APD along with the signal.

The PIN diode is characterized by an efficiency, η, in units of ma (detected) per mw (optical) input. Typically η is defined and measured to include the loss of the connector and fiber pigtail. A PIN diode is typically modeled as a current source, shunted by a parasitic capacitance. The bandwidth of this current source is much larger then the CATV spectrum and is not of concern, although the parasitics in the package will combine with other receiver components to limit the overall system performance.

3.5 Amplifiers

Amplifiers and drivers are used at various points in the overall system to match the typical CATV RF levels to those appropriate for laser based systems. These amplifiers are conceptually no different from units used in COAX amplifiers, and are likewise characterized for noise figure, linearity and bandwidth performance. The required performance will be discussed as part of the actual analysis of a laser based trunk, to follow.

4. CATV TRUNK APPLICATIONS - PERFORMANCE CRITERIA

The key performance criteria [2] for CATV trunk applications are:

C/N - Carrier to Noise. The dB ratio of the peak carrier power for a given channel to the noise floor near that carrier, assuming a noise bandwidth of 4 MHz.

CTB - Composite Triple Beat. The dB ratio of the peak carrier to the peak power in the composite third order intermodulation tone which for CATV signals appears at the carrier frequency.

CSO - Composite Second Order. The dB ratio of the peak carrier to the peak power in the composite second order intermodulation tone. For standard and IRC frequency plans, the CSO appears at the carrier ± 1.25 MHz. For the HRC frequency plan, the CSO beats appear at the same frequency with the CTB beats.

We will look at C/N and intermodulation performance separately, since the noise performance of most components is well understood and may be accurately modeled. Intermodulation performance, on the other hand, must be measured and characterized on each individual unit.

5. C/N - NOISE SOURCES IN A FIBER OPTIC AM LINK

We will use the model [3] shown in Figure 4 to discuss noise sources. Regardless of source, we are ultimately interested in the total noise present at the input to the front end amplifier at the receiver. This approach also makes comparisons among these sources simpler. There are three dominant noise sources, modeled here as current sources since the receiver diode (PIN) is modeled as an ideal current source. We review these noise sources in detail below.

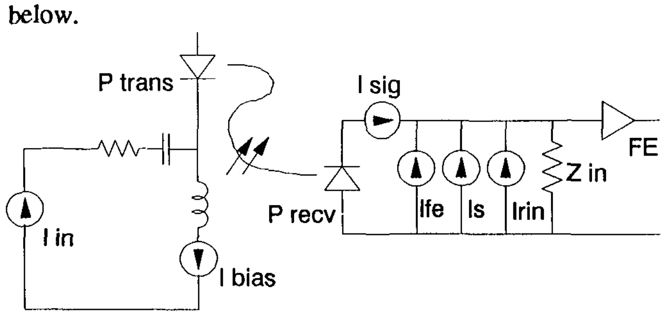


Figure 4

5.1 Front End Noise

All electronic amplifiers add noise to the input signal when delivering the output to a load. In RF systems, we typically deal with an amplifier in terms of its Noise Figure, a measure of the equivalent noise power that appears at the input. For this analysis, that noise power is converted to an equivalent current, commonly expressed in picoamperes per square root of Hertz ($pa/\sqrt{Hz}$) .

The equivalent input noise is a function of many circuit and device parameters. It is generally not flat across the frequency spectrum of interest, may vary with temperature and load conditions. It must be characterized for each device or family of devices considered for use.

Low noise digital fiber optic system receivers have achieved equivalent input noise currents in the 3-5 $pa/\sqrt{Hz}$ range, although these receivers are typically limited in their RF output capability and are not yet useful in broadband CATV applications. Amplifiers useful for these broadband applications are more typically in the 12-16 $pa/\sqrt{Hz}$ range. Further improvements in this performance can be expected as CATV applications expand the need.

5.2 Shot Noise

The conversion of light energy, which arrives at the PIN junction in photon "packets", each at a particular energy level, to an electrical current flow involves the generation of hole-election pairs in the Intrinsic junction region as the discrete photon energy "packets" are absorbed. The effectiveness of this conversion is a statistical function and the deviation from perfect conversion is referred to as quantum or shot noise on the detected signal. It is given by:

$$\overline{i_s^2} = 2e\,Ip \quad A^2/Hz$$

where e = charge on electron

Ip = detected current

This noise is assumed to be spectrally flat over the CATV region of interest. Shot noise represents a fundamental limit on overall noise performance, to be asymptotically approached as other noise sources are reduced through improved device performance.

5.3 Relative Intensity Noise - RIN

The final dominant noise source, in the AM system, is laser intensity noise. When observed at the receiver, RIN is a function of many electro-optic and optical mechanisms, including

- Quantum effects in electron to photon conversion in the laser
- Reflection effects on the laser cavity
- Mode partitioning and modal dispersion
- Phase noise to intensity noise conversion in external reflective cavities.

RIN is a device performance parameter and must be specified and measured for each device. Because it is critically dependent on the optical circuit configuration, it is important to carefully specify and characterize the test setup when measuring laser RIN. In addition, intensity noise has a potential for significant spectral shaping, depending on the dominant source of intensity variation. Reflection induced intensity noise can be particularly frequency dependent due to transit times between the reflectors and the source.

Typical multimode (Fabry-Perot) digital system lasers have RIN performance in the -110 to -140 dB/Hz range, and laser noise is of little concern with respect to error rate performance. For AM CATV applications, RIN must be better than -145 dB/Hz for typical system applications. We have routinely achieved RIN performance from distributed feedback (DFB) lasers, with optical isolators, that span the range of performance from -148 to -152 dB/Hz in system level applications.

5.4 Noise Measurement and C/N

When viewed as equivalent unity bandwidth current sources, it is relatively easy to separate the total noise power into its component parts. First we assume:

$$\overline{i_{tot}^2} = \overline{i_{FE}^2} + \overline{i_S^2} + \overline{i_{RIN}^2}$$

The frontend noise power, $\overline{i_{FE}^2}$, is independent of the presence of an input optical signal and hence may be measured with the laser shut off. Secondly, the shot noise is a function of the DC detector current and may be calculated under those conditions. The RIN component then is derived by subtracting the $\overline{i_{FE}^2}$ and $\overline{i_S^2}$ components from the total. Device data sheets typically specify laser RIN as a dB ratio, so:

$$RIN = 10 \log \left[\frac{\overline{i_{RIN}^2}}{\eta P_o^2} \right] \qquad dB/Hz$$

To obtain the C/N ratio, we now must look at the achievable per channel carrier amplitude. Referring back to Figure 2a, our signal is modeled as a sum of N equal amplitude sine waves.

$$P_{TRANS}(t) = P_{cw} \left[1 + \sum_{i=1}^{N} m_i \cos(\omega_i t + \phi_i) \right]$$

Each channel i has a unique frequency defined by the frequency plan in use (STD, HRC or IRC), and even if phase locking HRC and IRC are used some random phase ϕ_i will be introduced by electronics and combiner cabling. For large N, N > 40 or so, we will therefore assume that the resulting amplitude distribution for P_{TRANS} is Gaussian. If we further assume that we do not wish to exceed the laser threshold with probability > .1%, the L-I characteristic shown in Figure 3a limits the achievable index of modulation, m_i, to about 4.4% for N=42 channels. In general, given m_i for a channel, the rms carrier power is given by:

$$C = \frac{m_i}{\sqrt{2}} P_{RECV} \cdot \eta \qquad ma,rms \text{ for } \eta \text{ in } ma/mw$$

and

$$C/N = 10 log \left[\frac{C^2}{\left[\overline{i_{tot}} \cdot 10^{-9} ma/pa \right]^2} \right]$$

We will defer a detailed look at this equation until intermodulation is discussed, since it directly impacts the achievable index of modulation, m_i.

6. INTERMODULATION NOISE - CTB and CSO

The theory and mathematics of intermodulation noise were well developed [4] in the early days of broadband (relative) linear telephony and further analyzed in the early days of CATV[5], when channel loads on COAX began to exceed the original 13 off-air channels.

Basically, if we model the transfer characteristic of any transducer (amplifier, laser, detector, etc...) as a third order polynomial $e_{out} = a_1 e_{in} + a_2 e_{in}^2 + a_3 e_{in}^3$ and apply our

$$P_{TRANS}(t) = \sum_{i=1}^{N} m_i \cos(\omega_i t)$$

signal spectrum, the resultant e_{out} is shown to consist of linear terms plus countable intermodulation products at frequencies related to $\omega_1 \pm \omega_2$ due to $a_2 e_{in}^2$ expansion (second order non linearity) and $\omega_1 \pm \omega_2 \pm \omega_3$ due to $a_3 e_{in}^3$ expansion (third order non-linearity).

In CATV, unlike telephony, the energy in each channel is highly concentrated at the carrier frequency, resulting in intermodulation products which fall in very narrow frequency ranges.

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The composite power in these frequency bands, a power based summation of the intermodulation products, is measured as the CSO (Composite Second Order) and CTB (Composite Third Order), interference power. It is normally measured relative to the carrier peak and reported in dBc, dB relative to the carrier.

Each composite second or third order beat is theoretically made up of a countable number of equal amplitude beats, assuming that the generating spectrum is flat, or in other words, $m_i = m_j$ for all i, j. If we assume that these beats are uncorrelated in frequency and phase, then the expected channel to channel relative differences in intermodulation performance will follow 10 log (N), where N is the number of second or third order products. In Figure 5a, we show a plot of the predicted second order intermodulation performance, for 42 CATV channels. In Figure 5b, we show a similar plot for third order beats.

In a real laser system, the achievable index of modulation, m_i, will be governed by the second and third order distortion coefficients a_2 and a_3 above, rather than by the simple Gaussian-threshold relationship reviewed in the idealized look at achievable carrier to noise performance above. We have achieved system level performance with indices, m_i, in the typical range of 2.5% to 5% .

7. TYPICAL RESULTS

In Figures 6a, b, c and d, we summarize the results of measurements on a 42 channel laser trunk link. Figure 6a is a spectrum analyser plot for a typical channel under test, showing the carrier , noise floor and second and third order composite intermodulation tones and the measurement results. Figure 6b is a derivation of the specific noise and device performance characteristics from those measurements. Figures 6c and 6d plot the broadband performance of the device on the theoretical $10\log(N)$ plots presented in Figures 5a and 5b. Measured parameters and broadband results can be compared with the theory and models above.

During the presentation, we will look at more statistical data from the Laser Link ™ units delivered to CATV MSOs during the first Quarter of 1989.

8. SUMMARY

We have reviewed many of the performance degradations and system considerations which are key to the application of AM modulated lasers in the CATV trunk networks. While the overall application is still in its infancy, these performance models will provide a foundation for unit to unit comparisons as well as evolutionary trends.

9. ACKNOWLEDGEMENTS

Credit is due to many members of staff in AT&T Bell Labs for their support and ideas in attacking these issues. I would like to particularly mention G. L. Fenderson and M. S. Schaefer who helped on the refinement of these models and the development of real hardware to test them.

I would also like to thank those members of the CATV engineering community who have openly shared their ideas, needs, techniques and time in helping our efforts. In no particular order, special mention to Louis Williamson, Dave Pangrac, Jim Chiddix, "Shorty" Coreylle, Tom Elliott, Richard "Rex" Rexroate, Dick Kreeger, Jack Ramsayer, John Walsh, Jim Hayworth, Bob Luff and Hugh Bramble.

REFERENCES

1. Several Papers in Session "Fiber Optics and Cable:Present and Future Trends", in NCTA '88 Technical Papers,1988.
2. For a complete look at CATV Trunk requirements and measurement techniques, see "NCTA Recommended Practices for measurements on cable television systems", National Cable Television Association,First Edition,1983.
3. See Senior,John M.:"Optical Fiber Communications: Principles and Practice",Prentice-Hall International Series in Optoelectronics,ISBN 0-13-638248-7,1985 for a general treatment of Analog Fiber Transmission alternatives.
4. Members of the Technical Staff,Bell Telephone Laboratories: "Transmission Systems for Communications",Fifth Edition,1982.
5. Simons,K:"The Fundamentals of Distortion in CATV Amplifiers",Jerrold Electronics Corporation,1967.

CATV TRUNK LIGHTWAVE SYSTEM
Intermodulation Analysis - Composite Second Order (CSO)

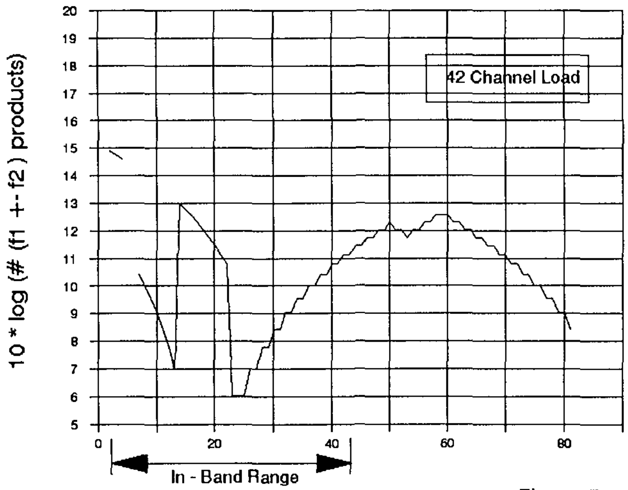

Figure 5a

CATV TRUNK LIGHTWAVE SYSTEM
Intermodulation Analysis - Composite Triple Beat (CTB)

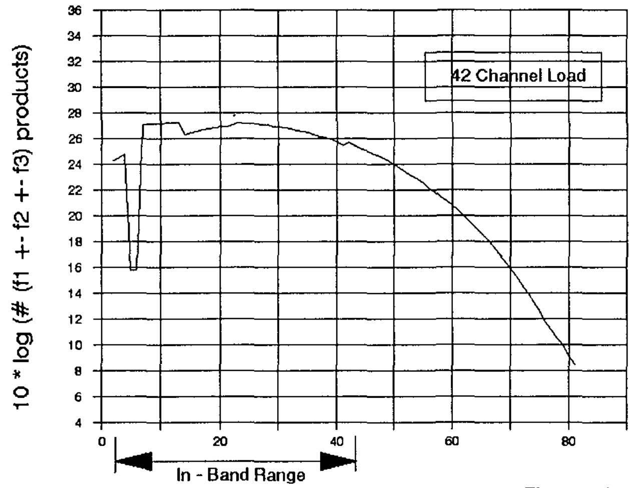

Figure 5b

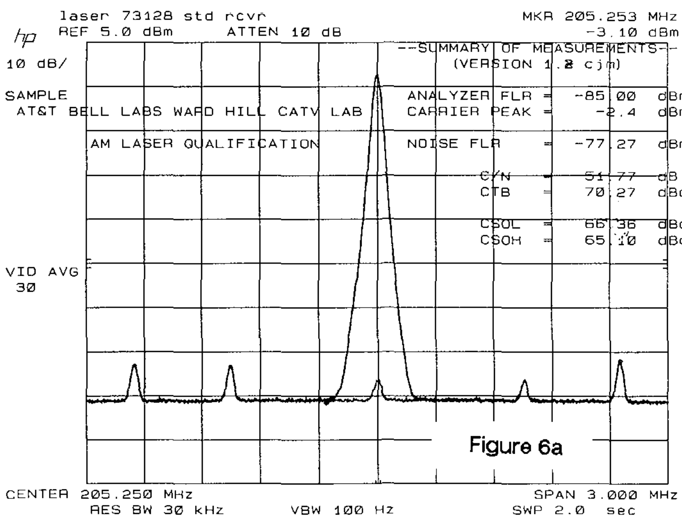

Figure 6a

AT&T Bell Laboratories CATV Trunk Design

Fiber Loss - dB =	5.15			12:06 PM
Received Opt Power - dBm =	-4.05			
PIN (standard)		Calculations -->		
Detected curent - ma =	0.345	Responsivity ma/mw =	0.877	
Signal power out-dBm =	-48.2	Index of Mod =	0.071	
at Impedance - ohms =	50			
SYSTEM (Under Test)		Calculations -->		
Analyzer floor dBm/Hz =	-131.90			
Analyzer Impedance ohms	75.00			
PIN detected current-ma =	0.316	GB2 Effective Gain dB =	15.20	
Tone Out GB2 - dBm =	-4.2	GB1 Effective Gain dB =	9.70	
Tone Out GB1 - dBm =	-19.4	NF GB1 + GB2 dB =	12.63	
Tone Out FE - dBm =	-29.1	FE Transimpedance ohms=	602.76	
Noise GB1+GB2 - dBm/Hz =	-130.60	FE Noise pa/sqrtHz =	12.37	
Noise Nolite GB2 dBm/Hz =	-125.00	LASER RIN dB/Hz =	-150.92	
Noise FE+GB1+GB2 dBm/Hz =	-122.30	C/N FE OUT dB =	52.77	

Figure 6b

CATV TRUNK LIGHTWAVE SYSTEM
Intermodulation Analysis - Composite Second Order (CSO)

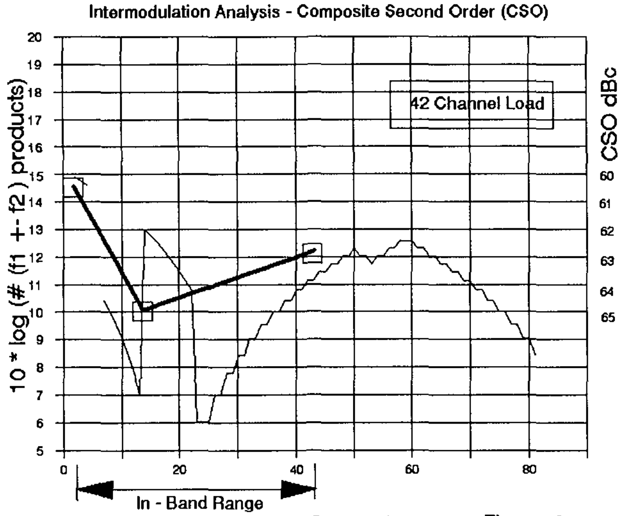

Figure 6c

CATV TRUNK LIGHTWAVE SYSTEM
Intermodulation Analysis - Composite Triple Beat (CTB)

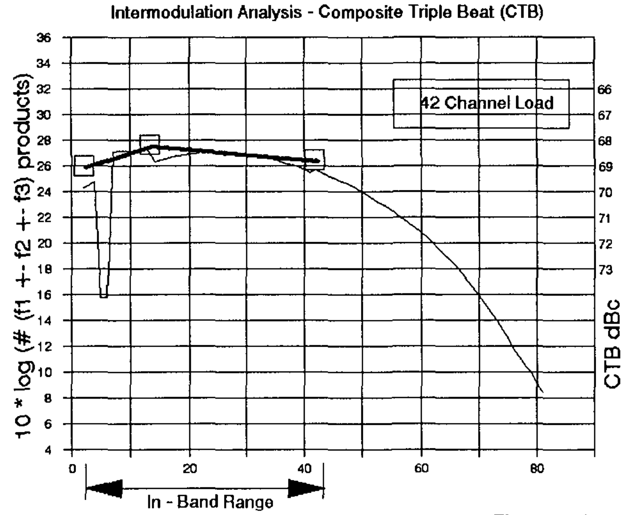

Figure 6d