COMPOSITE TRIPLE BEAT AND NOISE IN A FIBER OPTIC LINK USING LASER DIODES

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ABSTRACT

Using a Laser diode in an analog multichannel fiber optic link Composite Triple beat and Carrier to Noise ratios are calculated as a function of laser parameters as well as of the number of channels. Two models for the nonlinearities of a laserdiode are used. The results are applied to multichannel Vestigial Sideband transmission.

INTRODUCTION

The low loss of optical fibers (0.5 dB/km versus 30 dB/km of coax) makes them an attractive choice for multichannel TV transmission. Single mode fiber technology offers up to 1 GHz transmission bandwidth at reasonable cost. Modal noise problems that plagued older multimode systems are non existent in single mode designs. The choice of the modulation format for the transmission of multichannel video is heavily dependent on the parameters of an optical link in terms of noise, intermodulation distortion, and loss budgets. Frequency modulation has been successful when noise levels were high (because backreflection problems were not fully understood and because of high RIN in the lasers themselves). Improvements in laser technology and the capability to avoid backreflection noise allow the use of a Vestigial Sideband modulation format. This approach is very attractive, because no modulation conversion (which is costly or of limited quality) has to be done.

The optical link seen as an RF communication link

Every RF link (microwave, coaxial CATV trunk or supertrunk etc.) can be analyzed for analog transmission, when the following parameters are known:

- The noise figure
- The intermodulation characteristics
- The compression power

It is interesting to ask if these parameters can be found for a link including optical components (lasers, PIN detectors etc.) too.

Noise

The few laser manufacturers that specify noise for their lasers do this by using the RIN number (Relative Intensity Noise) [1, Guekos 1983]. RIN can be considered to be the noise floor, measurable with a spectrum analyzer after light to current conversion with an optical detector.

To find the carrier to noise ratio we consider the following: We talk about 100% depth of intensity modulation of the light when an RF signal that is superimposed to the bias reaches the lasing threshold with its peaks (see figure 1). RIN can therefore be considered a peak carrier to noise density ratio.

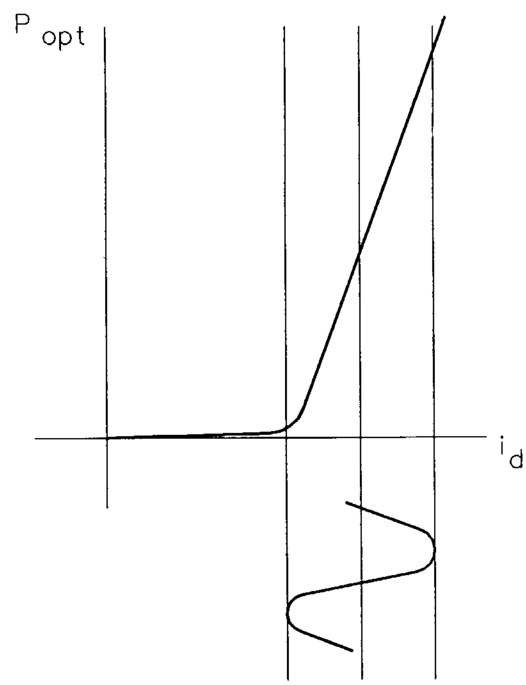

Figure 1: 100% intensity modulation of a laser diode

The carrier to noise (density) ratio CNR when the depth of modulation is 100 % is

$$CNR = -RIN-3 \qquad (dB) \qquad (1)$$

The noise figure F of the laser can be found when the CNR at the input of the laser is known. The RF drive level is determined with the differential quantum efficiency E of the laser, which is

$$E = d(P_{opt})/d(i_d) \qquad (2)$$

with P_{opt} : Optical power

i_d : Laser diode current

The RF drive level C for m = 100% is

$$C = (i_{bias}/\sqrt{2})^2 Z \qquad (3a)$$

with i_{bias} : Laser bias current

Z : Resistor in series with the laser diode (75 Ohm)

Using equation (2) in equation (3a) and the bias current as the differential drive current, we find

$$C = (P_{opt}/E)^2 Z/2 \qquad (3b)$$

The noise power N_L referred to the input of a laser diode exceeds kT_0 by the noise figure of the laser:

$$N_L = -174 + F \qquad (dBm) \qquad (4)$$

With the definition of the CNR

$$CNR = 10 \cdot \log(P_C/P_N) = C-N \qquad (dB) \qquad (5)$$

we find that

$$N = C - CNR \qquad (dB) \qquad (6)$$

With $10 \cdot \log(kT_0) = -174$ dBm/Hz and using equation (4) and equation (3) we find F to be

$$F_L = 10\log[(P_{opt}/E)^2 Z/2] + RIN + 207 \quad (dB) \qquad (7)$$

A good laser diode can have a -145 dB/Hz RIN number. With a typical differential efficiency of 0.04 W/A and an output power of 1 mW we find the laser noise figure to be 46 dB in a 75 Ohm system.

Intermodulation Distortions

The nonlinear distortion of the laser transfer characteristic produces intermodulation products in an analog multicarrier system.

To determine distortion levels in a weakly nonlinear region around the bias point it is sufficient to specify the 2nd and 3rd order input intercept point (IP) of a laser. The third order IP can be found by driving the laser with two RF carriers with a total depth of modulation of less than 50%. A PIN detector will show the following spectrum (figure 2):

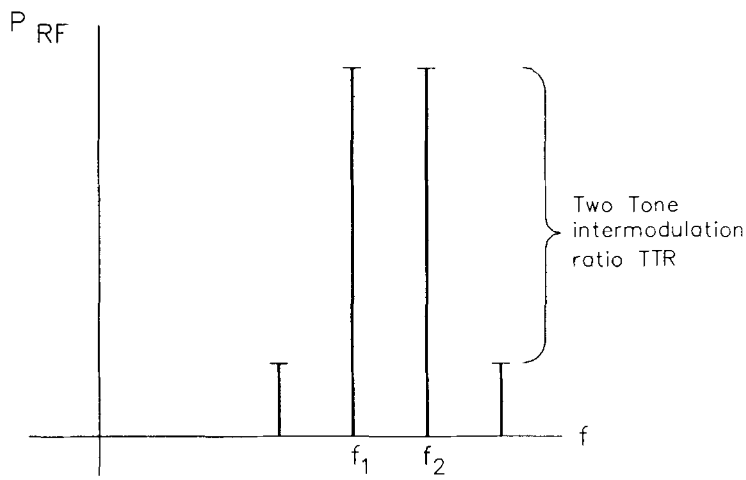

Figure 2: Two tone third order intermodulation test of the laser.

The 3rd order Input Intercept point $IP3_{in}$ is defined [2, Hayward 1982] as

$$IP3_{in} = C_{in} + TTR/2 \qquad (dBm) \qquad (8)$$

The Triple Beat Ratio (TBR) is 6 dB lower than the Two Tone Ratio (TTR), shown in figure 2. Equation (9) shows how to find the TBR when an Intercept point is known:

$$TBR = TTR-6 = 2(IP3_{in} - C_{in})-6 \qquad (dB) \qquad (9)$$

A Dynamic Range figure D allows the comparison of different RF link components with respect to CNR and channel loading. It is insensitive to the input level into the device under consideration:

$$D = IP3_{in}/2 - F \qquad (dB) \qquad (10)$$

Let us compare a laser diode to a cascade of 20 coaxial amplifiers (each at a gain of 20 dB to compensate the loss of a coaxial cable):

	Laser	Coax Amps
F:	46 dB	22 dB
$IP3_{in}$:	25 dBm	11 dBm
D :	-33.5 dB	-16.5 dB

This laser(RIN = -145 dB/Hz, $IP3_{in}$ = 25 dBm, E = 0.04A/W, and P_{opt} = 1 mW) has a dynamic range of 17 dB less than a standard coax amplifier cascade with 20 dB of gain per amplifier. Distributed Feedback Lasers (DFB's), can have RIN's as low as -155 dB/Hz. Their Dynamic Range is therefore only about 7 dB lower than that of the above mentioned coax amplifier cascade. The conclusion that today's lasers are becoming as good as coax amplifiers is not necessarily correct. First we have to answer the following questions:

- Is the 3rd order intercept point a sufficient description of 3rd order nonlinearity?
- What about second order distortions?
- Under what conditions do we really get the low noise of the latest laser diodes?
- How do systems architectures compare between fiber and coax?

Here are possible answers:

<u>Is the 3rd order intercept point a sufficient description of 3rd order nonlinearity?</u>

The answer is no when a multichannel CATV signal is used. Let's first look at a typical bridger amplifier. Some manufacturers recommend to operate them at a 51 dBmV level with 54 channels. At one (very improbable) time all 54 carriers will be at maximum amplitude. The peak to peak sum voltage at one output transistor is then 2·54·355 mV or 27V. Those hybrids operate from 24V. Therefore, at times that are statistically very rare, this hybrid amplifier is driven into saturation. The same could be true for a laser. When the RF drive current hits the lasing threshold or when it hits the high power region where the differential quantum efficiency rolls off, we leave the weakly nonlinear region described by the third order intercept point. Figure 3 compares the two devices.

How to deal with this quantitatively? Coaxial CATV amplifier manufacturers measure intermodulation distortion (composite triple beat) under real life conditions or with a Dix Hill signal generator. The same can be done with a laser. Nevertheless, it is possible to make some predictions of the distortion products of a laser when two laser models are used:

Model 1: The laser has no compression and is adequately described by its third order intercept point (and other laser data).

Model 2: The laser is perfectly linear with the exception of the compression at the lasing threshold.

The distortion products of both models can be calculated:

<u>Model 1</u>

It is generally agreed that the correct way of specifying third order distortion in CATV is the Composite Triple Beat Ratio (CBR) [3, Jeffers 1980]. Let's derive a CBR when the 3rd order intercept point is known:

The Composite Triple Beat Ratio (CBR) for multiple carriers is

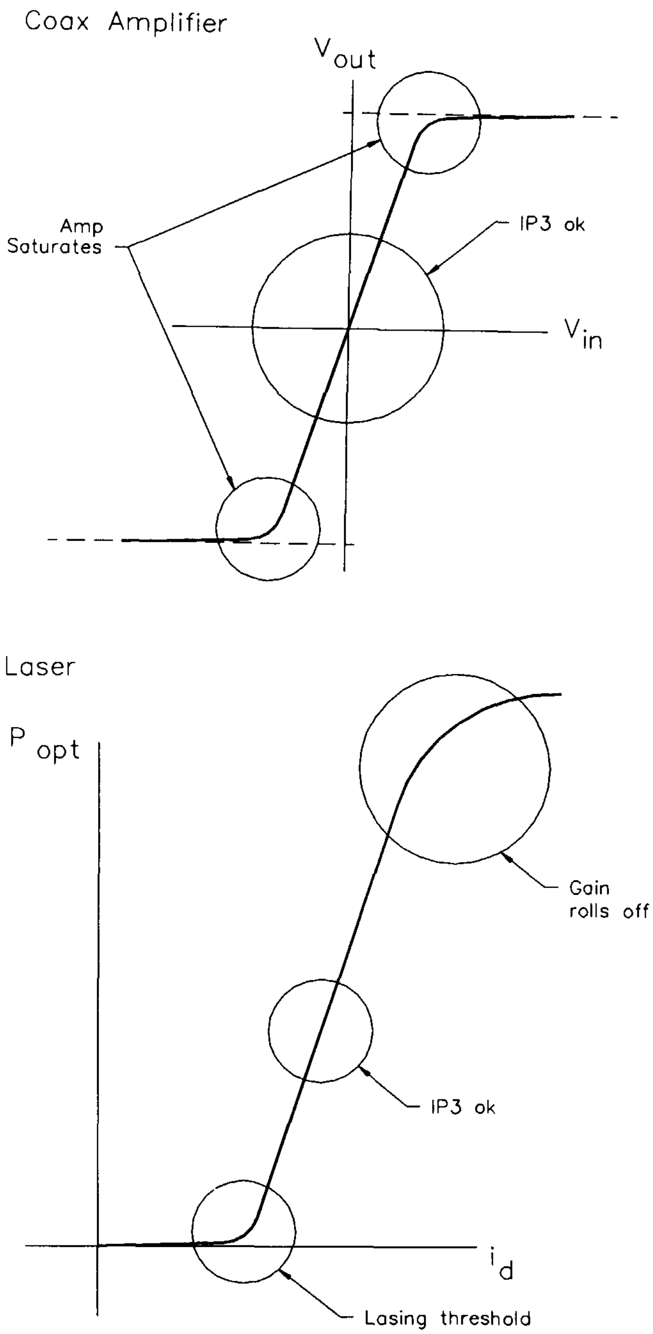

Figure 3: Nonlinear regions of coax amplifier and laser

$$\begin{aligned} CBR &= TBR - K \log Ch \\ &= TTR - 6 - K \log Ch \qquad (dB) \end{aligned} \tag{11}$$

with Ch: Number of channels

TBR: Triple Beat Ratio

TTR: Two Tone Inermod. Ratio

K: Constant

The constant K is equal or less than 23 [4, Afsar 1987]. Using the Intercept Point number, we find with equation (9)

$$CBR = 2(IP3-C) - 6 - K \log Ch \qquad (dB) \tag{12}$$

It is useful to ask for the carrier to noise ratio for a varying number of channels when composite triple beat is below the limit of perceptibility (CBR ≅ 60 dB). Using equation (5) (C = CNR + N) in equation (12) we find

$$CNR = IP3-F+108-(CBR+6+K \log Ch)/2 \tag{13}$$

With the above laser, CBR = 60 dB, K = 18, and 10 channels we get a CNR of 45 dB.

If these carriers are amplitude modulated (vestigial sideband) with a 50% APL video signal, then their average power is 6 to 8 dB lower than their power at sync time. We can therefore drive the laser 6 dB higher and now get a CNR of 51 dB for 10 channels.

<u>Model 2</u>

We assume that the laser is totally linear with the exception of the threshold region (we neglect compression at high optical power levels). From the considerations on RIN we know that

$$CNR = -RIN - 3 \text{ dB}$$

for 1 carrier and 100% depth of intensity modulation. If the sum RF current must not exceed the threshold region then we have to reduce the RF drive level by 20logCh (Ch = number of channels). Therefore

$$CNR(Ch) = -RIN-3-10\log 4.2MHz-20\log Ch \quad (14)$$

The above laser with an RIN of -145 dB/Hz will therefore have a 10 channel CNR of

$$CNR(10) = 145-3-66-20 = 56 \text{ dB}$$

when this model is used.

Figure 4 shows CNR for Model 1 and Model 2 as a function of the number of channels. The upper curve is for the case that the modulation is Vestigial Sideband (or AM), the lower trace is for unmodulated carriers.

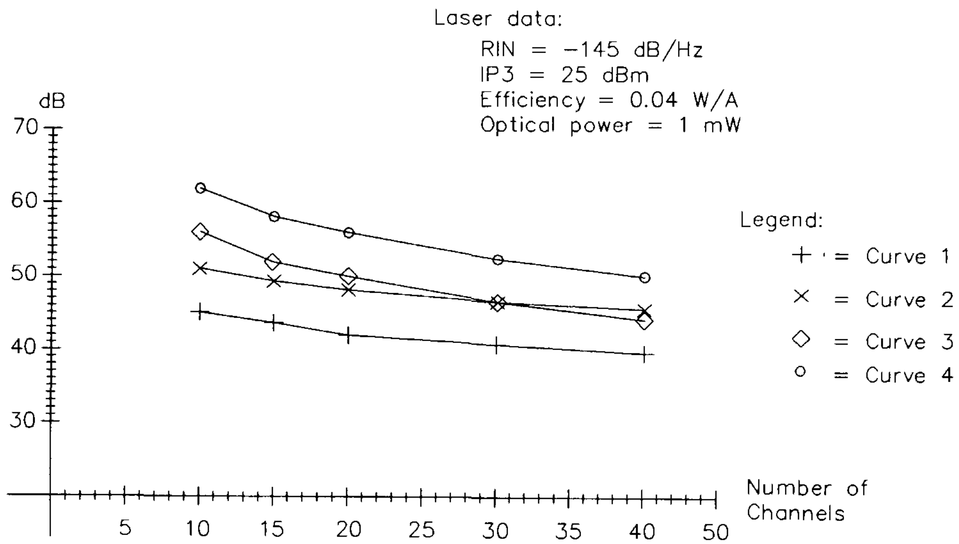

Figure 4: CNR for Model 1 and Model 2 as a function of the number of carriers (channels)

What about second order distortion?

When standard frequencies for Vestigial Sideband transmission are used the second order difference products fall 1.25 MHz below other visual carriers and cause therefore no visible impairment. The second order sum products fall 1.25 MHz above other visual carriers and cause very visible luminance interference.

In the late 60's increasing numbers of channels made second order products of single ended amplifiers the biggest limitation of CATV. The introduction of push-pull amplifiers solved that problem [5, Lambert 1970]. Lasers suffer from the same second order distortion. Lasers can be designed to have low third order distortions but this does not necessarily affect second order products. Push-pull lasers are unknown and it seems that we have to live for some time with those distortions. Two approaches can be used to solve this problem:

- The Octave System
- The Split Band System
- HRC

In the Octave System, the channels are converted to a higher frequency where they do not exceed an octave anymore. Second order products fall then above or below the frequency range occupied by the channels.

In the Split Band System one laser can transmit the Low Band (54...88 MHz) and the High Band (174...216 MHz). All second order products fall above, below, or between the two bands. A second laser transmits the Mid Band (120...174 MHz), which is less than an octave. And a third laser transmits the Super Band (216...294 MHz). If more channels are needed, a fourth fiber might be used for the Hyper Band as is shown in Figure 5.

When HRC (Harmonically Related Carriers, all carriers are phase locked to a common frequency reference) is used second as well as third order products fall with no frequency offset on top of visual carriers. When phase noise is low the visibility of such an impairment is very low. HRC has been used to fight composite triple beat but it can also be very useful to reduce second order interference in a single ended system like a laser diode.

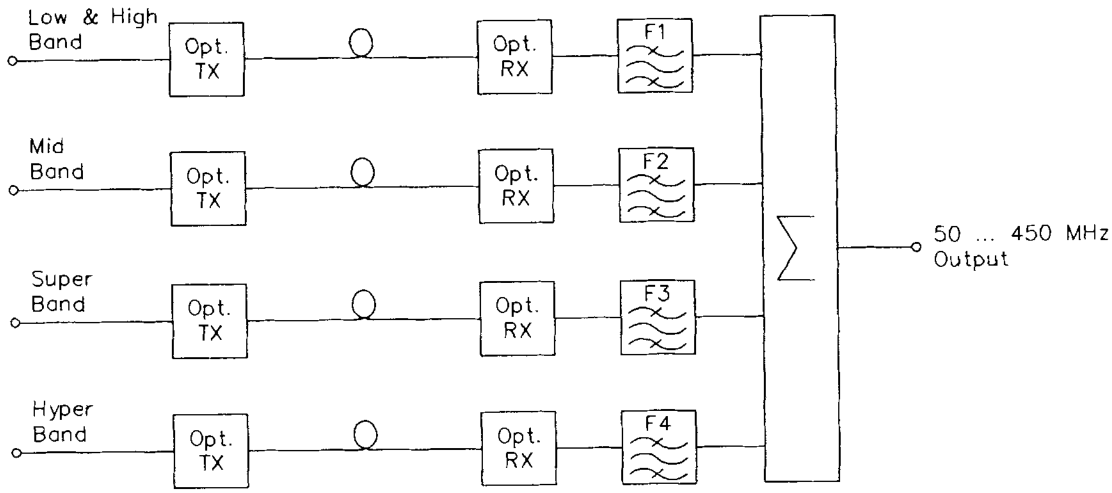

Figure 5: A CATV fiber optics link for Vestigial Sideband modulation avoiding second order distortion

Under what conditions do we really get the low noise of the latest laser diodes?

The RIN of a laser is highly dependent on the amount of light that is reflected back into the laser [6, Ohnishi 1983]. The following sources of back reflections can be found:

- Reflections inside the laser
- Reflections in the connectors
- Reflections in the splices
- Reflections in the detector

Reflections inside the laser are out of our control. Reflections in connectors can be kept low if special high return loss connectors are used. The state of the art is a 55 dB return loss. Principles as described in [7, Rao and Cook 1986] are used. Another method is to avoid connectors totally and fusion splice the entire system. Reflections in splices can be avoided when fusion splices or low loss rotary splices are used. Reflections in detectors are hard to avoid, unless the manufacturer takes special measures to couple the light from the pigtail to the photodetector like antireflective coating and polishing the fiber at an angle. All reflection problems can be solved when an optical isolator is used directly after the laser [1, Guekos 1983].

Another problem is receiver noise. We can ask at what optical receive power the contribution of receiver quantum noise is equal to RIN. At this power level video SNR will be degraded by 3 dB.

When RIN is predominant CNR is in a 1 Hz bandwidth and for 100% depth of modulation:

$$CNR = -RIN - 3 \qquad \text{(dB)}$$

When quantum noise is predominant CNR is for the same bandwidth and modulation [8, Keiser 1983]:

$$CNR = R_0 P_r / 4q \qquad \text{(dB)} \qquad (15)$$

with R_0: Detector Responsivity

P_r: Received optical power

q: $1.6 10^{-19}$

We get a 3 dB systems CNR degradation when

$$-RIN - 3 = 10\log(R_0 P_r / 4q) \qquad \text{(dB)} \qquad (16)$$

Solving equation (16) for P_r:

$$P_r = (4q/2R_0 10^{-RIN/10}) \qquad \text{(dBm)} \qquad (17)$$

With $R_0 = 75\%$ and RIN = -145 dB/Hz, we get

a receive power of 0.135 mW or -9 dBm.

With the above laser diode (1mW optical output power) we would therefore get a 51-3=48 dB CNR after 9 dB of optical loss for a CBR of 60 dB and for 10 channels.

It becomes apparent that today's 1 mW lasers are not powerful enough for high optical loss budgets.

Another question is: How does a calculated CBR compare to a measured one? Here we open a door to misunderstandings. Nobody measures CBR's with a true power meter for the reason that a spectrum analyzer is a more convenient tool. This instrument contains a logarithmic amplifier followed by a peak detector.

Therefore, correction factors can be calculated when the statistics of the noise are known. For Gaussian noise and for Bessel IF filters this is 2.5 dB. If we assume that composite triple beat noise has a similar correction factor (it is essentially narrowband noise), then we can measure a 1.3 dB higher CNR for a given (rms-power) CBR.

<u>Comparison of theoretical results with measured results</u>

We have experienced that measured results are normally better than what theory predicts. Possible reasons are:

- The constant K in equation (11) can be lower than 23, resulting in a lower CBR than predicted by equation (11).

- Some lasers are operated around their inflection point of the laser transfer characteristic (the third derivative is zero and therefore third order products are zero). Hire an inflection point finder when you plan to use those lasers.

-RIN's are better than -145 dB/Hz. RIN's as high as -155 dB/Hz have been reported. A 10 dB better RIN allows a 10exp(10/23) ≈ 3 higher number of channels.

<u>How about the usefulness of HRC?</u>

HRC is in fact very useful in an optical link. When [9, Switzer 1975] was phase fideling in the 70's, he expected a somewhat higher HRC gain than was found later to be feasible in practice. A good explanation for that can be found in [10, Krick 1979]. An HRC signal has a peak envelope that is a function of the phase relationship between the individual carriers. Krick shows that the worst case peak envelope of a multichannel CATV signal can be 5 times higher than under optimum phase conditions. In a normal coax system this phase pattern changes along the trunk and so does the peak envelope, causing different amounts of intermodulation distortion along the trunk. In a cascade of amplifiers an optimum phase pattern or a minimum envelope can therefore hardly be maintained.

Since repeaters are very unlikely in an optical system using AM, one laser can take full advantage of an optimum phase pattern, therefore achieving full HRC gain.

<u>What has been done so far in AM on fiber?</u>

The Japanese have reported AM on fiber systems [11, Fujito 1985] and [12, Fujito 1988]. [13, Koscinski 1987] talked about linearisation principles. Similar methods have been published in [14, Straus 1977] also. Ortel showed a 40 channel system at the Western CATV Show 1987 in Anaheim. In 1988, more reliable data can be expected in regards to this subject.

<u>What progress can be expected in AM on fiber?</u>

Predistortion networks allow a substantial improvement of the linearity of the optical transmitter. It is not clear if improvements of the lasers themselves can not do the same. The goal will be to come as close as possible to an optical transmitter that behaves like the above mentioned model 2.

External modulation of the light intensity will become an issue when distortions of an external modulator are lower as when a laser is directly modulated. The insertion loss of an external modulator has to be small as long as the laser power is a limiting factor in systems architecture. See [15, Stephens 1987] about external modulators.

<u>How do system architectures compare between fiber and coax</u>

The newest developments in laser technology and in the use of single mode fiber have shown that substantial numbers of AM (vestigial sideband) or FM channels can be transmitted over fiber. The CATV operator should be aware of the difference between AM on fiber and AM on coax. It is improbable that AM on fiber can use repeaters in the same way as it is common practice with coax amplifiers. Therefore the architecture might be more in the direction of a star form. Today's lasers have too little power to allow branching as would be required in a tree network. This might change in the future.

<u>Conclusions</u>

Looking at a fiber optic link from an RF standpoint allows us to predict Composite Triple Beat and Noise with a reasonable degree of accuracy when multichannel VSB/AM signals are transmitted.

Semiconductor lasers have reached performance levels regarding linearity and low noise that make them a feasible choice for video multichannel VSB/AM transmission on fiber. Second order distortion levels are often a limiting factor. The frequency plan has to be chosen so that second order products do not produce visible interference. Higher optical transmit power levels than 1 mW will be needed, when optical loss budgets have to exceed a few dB and when CNR's close to 50 dB have to be achieved. Cost effective 450 MHz Vestigial Sideband fiber optic links using up to four fibers can be expected to be successfully installed in the near future.

Acknowledgements

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