# FEASIBILITY OF MULTI-CHANNEL VSB/AM TRANSMISSION ON FIBER OPTIC LINKS

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## ABSTRACT

Fiber optic supertrunks have already demonstrated the capability of transporting 8-16 video channels/wavelength over path distances greater than 20 km (repeaterless). These systems have traditionally utilized wideband FM as the RF modulation technique. Wideband FM provides the dual benefits of 1) signal to noise improvement and 2) high immunity to intermodulation distortion.

While the performance of these fiber optic (FO) links is impressive, they are also relatively costly (>$5K/channel not including FO cable). Additionally, the use of FM modulation requires a potential modulation conversion (AM/FM/AM) at both ends of the FO link with the attendant costs for AM modulators and demodulators. For many broadband transportation applications these costs are prohibitive and have prevented the widespread usage of FO links.

The ability to use multi-channel VSB/AM transmission is highly desirable. The ideal scenario would be to accept a broadband signal (bridger output etc.) and transport these signals directly over the fiber optics links without any modulation conversion.

The scope of this paper reviews the following areas:

- A Multi-channel VSB/AM Fiber Optic System Block Diagram.
- Basic VSB/AM System Considerations.
- Performance of a Multi-channel VSB/AM FO Link.
- Feasibility of Optimizing the Performance and Number of Channels on VSB/AM FO Links.

## INTRODUCTION

Fiber optic systems have been finding more and more applications where they provide the most cost effective solution. The majority of these applications pertain to digital communications. However, there are a large number of analog system applications for which fiber optic links are also being selected. The most common requirement for analog transmission on a fiber link is transportation of video signals. Although the video information could be converted to a digital signal prior to transmission, this is usually cost prohibitive. In many point to point applications, where repeaters are not required, fiber optic analog (FO) transmission systems can prove to be the most cost effective approach.

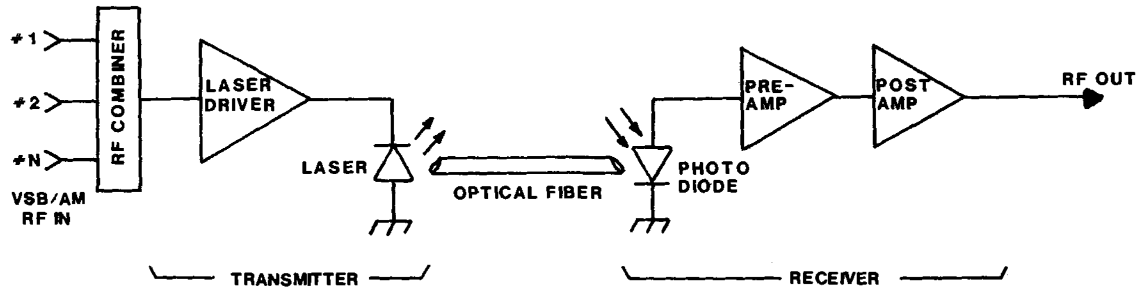
This paper focuses primarily on FO analog VSB/AM transmission applications for carrying multiple video signals over a fiber link. Cable television supertrunks and campus networks would be typical applications where these multichannel analog transmission systems would be utilized.

Although there are several types of lasers and fiber available, this discussion will deal exclusively with 1300 nm single mode lasers and single mode fibers. These selections are becoming de facto standards for optimum multi-channel FO analog systems since they provide low loss links which are immune from multimode noise phenomena (modal noise).

## MULTICHANNEL VSB/AM FIBER OPTIC SYSTEM

A block diagram for a multi-channel VSB/AM fiber optic link is illustrated in Fig. 1. The major system components are:

1) the optical transmitter, 2) fiber optic cable, and 3) the optical receiver.




**VSB/AM MULTI-CHANNEL FIBER OPTIC LINK**

**FIG. 1**

Optical Transmitter

An optical transmitter accepts the individual RF VSB/AM analog inputs and provides the signal conditioning necessary to drive a semiconductor laser diode. Fig. 2 shows the major optical transmitter components.

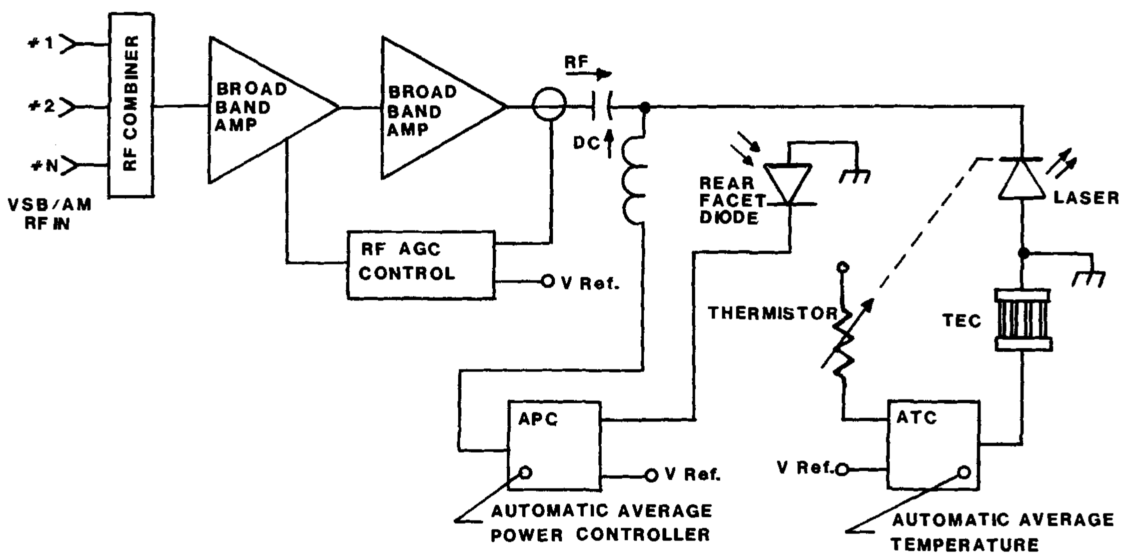
First, an RF combiner sums the multiple analog inputs which are to be transmitted. The RF levels for each carrier should be equalized prior to the optical transmitter. Otherwise, optimum noise and distortion performance for each carrier will not be achieved. However, a slope compensation stage may be provided after the combiner stage to adjust for normal cable slope effects.

Broadband amplifiers, AGC controlled, provide the necessary signal level to drive the laser diode. The RF drive level to the laser must be precisely controlled to realize the optimum system noise and distortion performance.

A d.c. bias is applied to the laser to provide a linear operating point. This d.c. bias current will determine the average optical output power out of the laser diode which is typically 0.5 mw for single mode 1300nm lasers.

Laser power is sensitive to changes in temperature and laser aging. To preserve a constant average optical output power, two control circuits are commonly provided in the laser transmitter; a laser temperature controller and an automatic optical power controller.

A photodiode monitors the rear facet of the laser as a sample of the transmitted optical power and uses this information to control the laser d.c. bias current. Thus, if the laser average optical power changes due to time or temperature, the laser bias is automatically adjusted to maintain constant average optical power.




**RF ANALOG OPTICAL TRANSMITTER**

**FIG. 2**

Laser life is adversely affected when operating at higher temperatures. Temperature control is accomplished by using a thermistor to monitor the laser temperature. A control circuit then drives a TEC (thermal electric cooler) to which the laser heatsink is mounted to maintain the laser at a constant temperature, typically 20 C).

Fiber Cable

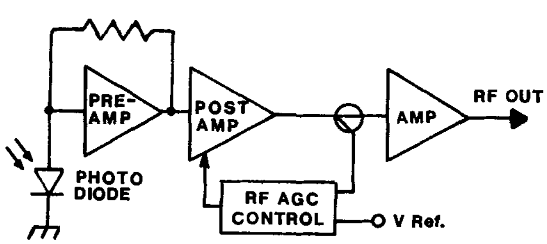
Single mode, 1300 nm, fiber cable is preferred for multi-channel analog systems. This fiber has a core diameter of only 9 um with an overall cladding/buffer diameter of 950 um (typical). These fibers may be assembled into various cable assemblies which provide multiple fibers, strain relief, and jacketing options.

Fiber cable is available in lengths up to several kilometers per reel. For distances greater than several kilometers, the fibers are typically fusion spliced to minimize path insertion losses. Single mode fusion splices have typical optical losses of only a few tenths of a dB. Single mode connectors have losses of 0.5 dB. The optical transmitter and receiver are normally connectorized for convenience in servicing equipment.

Optical Receiver

The primary function of an analog optical receiver is to reconvert the light power into an RF signal with a minimum contribution of noise and distortion.

An analog optical receiver block diagram is shown in Fig 3. The optical detector commonly employed for 1300 nm analog applications is either an InGaAs pin-diode or a Ge avalanche diode The major distinction between them is that the Ge avalanche diode has gain available (approx. 10) whereas the pin-diode has unity gain.




**RF ANALOG OPTICAL RECEIVER**

**FIG. 3**

The photodiode current drives a transimpedance pre-amp which provides high input sensitivity and converts the diode current into a voltage at its output. These preamps are available as DIP package devices with fiber pigtails attached.

A post amplifier, with AGC, follows the pre-amp to provide sufficient gain to obtain unity system gain for the entire FO link. AGC is utilized to maintain a constant output level independent of optical input power which may change due to fiber resplicing, fiber loss versus temperature etc.

BASIC VSB/AM
SYSTEM CONSIDERATIONS

The primary advantages of multi-channel VSB/AM transmission over multi-channel FM or digital FO systems are bandwidth efficiency and cost. A standard VSB/AM channel occupies a 6 MHz bandwidth whereas wideband FM uses 30 to 40 MHz of bandwidth per channel. Digital video requires even larger channel bandwidths for high quality video transmission.

System costs/channel for a VSB/AM FO system are also generally lower than a comparable FM or digital FO link. The major reason for this is the elimination of FM modems and digital codecs which are required when FM and digital FO links are employed. Fig. 4 illustrates the basic hardware differences for these three system approaches.

One might assume from this discussion that VSB/AM is being used extensively in multi-channel analog FO systems. However, this is not yet the case.

In spite of the availability of very wide bandwidth FO systems, the maximum number of VSB/AM channels which may be transmitted is limited by the optical source (laser transmitter) due to power loading and distortion constraints.

Semiconductor lasers currently provide maximum average optical output powers of -3 dBm. When a single carrier modulates the laser, all of the laser light power is dedicated to this one channel. As more carriers are loaded onto the laser, the corresponding optical power available per channel will be reduced since they all must share the finite available laser optical power. Assuming a constant average depth of modulation on the laser, the available optical power (per VSB/AM channel) degrades by 3 dB for each doubling of the number of channels transmitted. The result of lower transmitted carrier power is a corresponding reduction in carrier/noise ratio.

Depth of modulation of the laser is defined as the amount of current shift in the laser due to the modulation signal relative to the laser bias current. Fig. 5 illustrates this by showing a typical laser LI (light/current) curve. Increasing the depth of modulation of the laser will increase the effective (RF) transmitted laser power. This can be seen from the equation for total power launched by a semiconductor laser diode.

$$P(t) = Pb \left[1 + ms(t)\right] \quad (1)$$

where:

m = modulation depth
Pb = average laser optical power
s(t) = modulating signal (composite)

Increasing the modulation depth of the laser will also tend to increase the signal distortion. To control distortions in the optical output signal, the modulation must be confined to the linear region of the laser LI curve (Fig. 5). Typical m values for analog applications range from .25 to .50 depending on the linearity of the laser and system performance requirements.

Typical values of distortion for single mode lasers operating at 50% modulation depths are:

2nd orders : 30-45 dB
3rd orders : 45-60 dB

The spread in these values indicates that lasers do not necessarily have consistantly good linearity. Careful specification criteria and selection of lasers for analog parameters are very important to obtain high performance in multi-channel analog FO links.

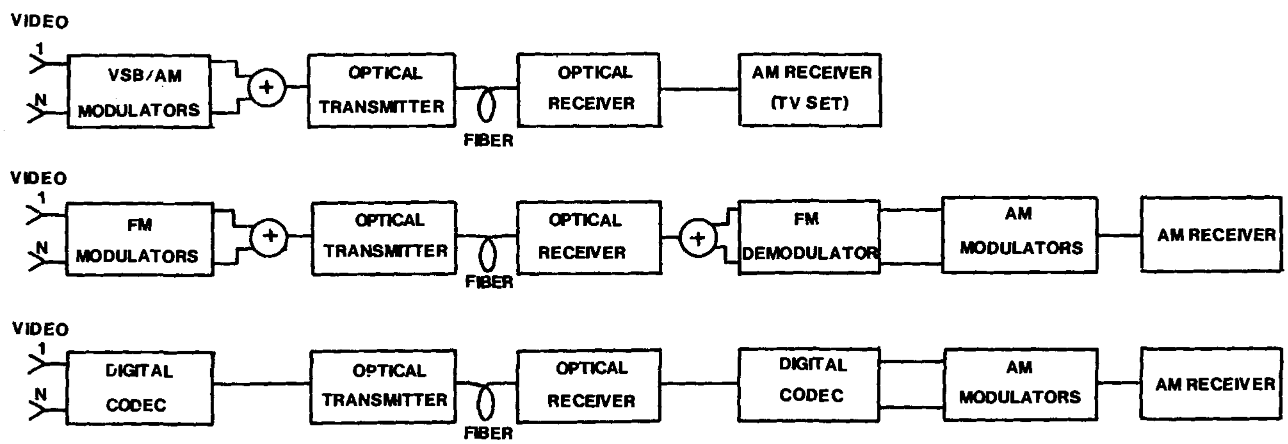
Due to the relatively high levels of distortions present (especially 2nd order) in semiconductor lasers, multi-channel VSB/AM systems may require careful spectrum planning. Schemes which avoid channel transmission where second orders are present may be required. One approach is to utilize only the upper octave of transmission bandwidth. Limiting the transmission bandwidth to the highest octave will allow all the second orders to land above or below the desired transmission spectrum (Fig. 6).

As can be understood from this discussion, a direct tradeoff exists between system distortion and carrier/noise performance as contributed by the optical source. Typical system performance will be reviewed by discussing a VSB/AM FO system which has been implemented recently by General Optronics.

## VSB SYSTEM APPLICATION

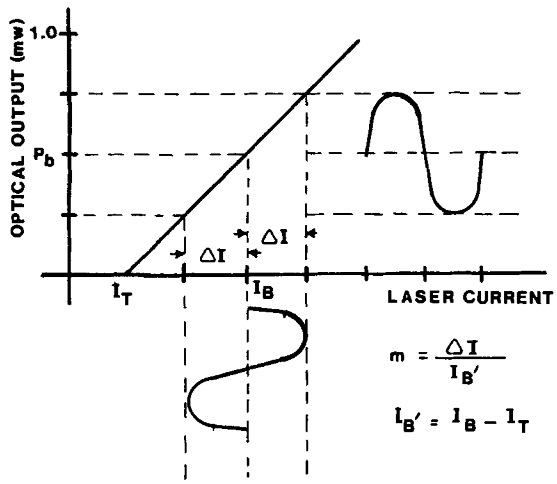
VSB/AM fiber optic systems have successfully transmitted 4 to 8 channels of video up to 12 km. Figure 7 illustrates the block diagram of a system installed for Seattle City Power & Light.

The application required transmission of channels 4, 5, 7, 9, 11 and the complete FM band over a distance of 12 km. Signal inputs to the fiber system were fed from a bridger amplifier output of a CATV system. The accessibility of the terrain required a repeaterless link which immediately ruled out extending the coax system. Microwave was also ruled out due to not having a line of sight available. Thus, a fiber optic link was selected as the implementation approach.




VSB/AM - FM - DIGITAL FO LINKS

FIG. 4



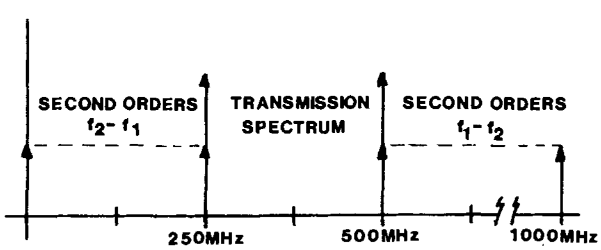

LASER L/I CURVE

FIG. 5

Two fiber optic links were utilized to transmit the 5 VHF channels and the FM radio signals. As shown in the block diagram (Fig. 7) the input signals were separated into the low VHF and high VHF bands with a VHF band splitter. Effectively three channels were carried on each fiber optic link. One link carried channels 7, 9, and 11. The second link carried channels 4, 5, and the FM band.

The optical transmitters are broadband (5-250 MHz) which accept RF input levels from 30 to 50 dBmV. AGC is included within the transmitter to provide a stable RF drive level to the laser. These transmitters employ single-mode semi-conductor laser diodes operating at 1300 nm wavelengths and launching average optical output powers of greater than -3 dBm.

The optical receivers employ wideband high sensitivity pin-fet preamplifiers. InGaAs pin-diodes are used as the opto-electronic conversion component. Post amplifiers with AGC provide stable output levels within the range of 30 to 50 dBmV.




SPECTRUM PLAN
TO AVOID SECOND ORDERS

FIG. 6

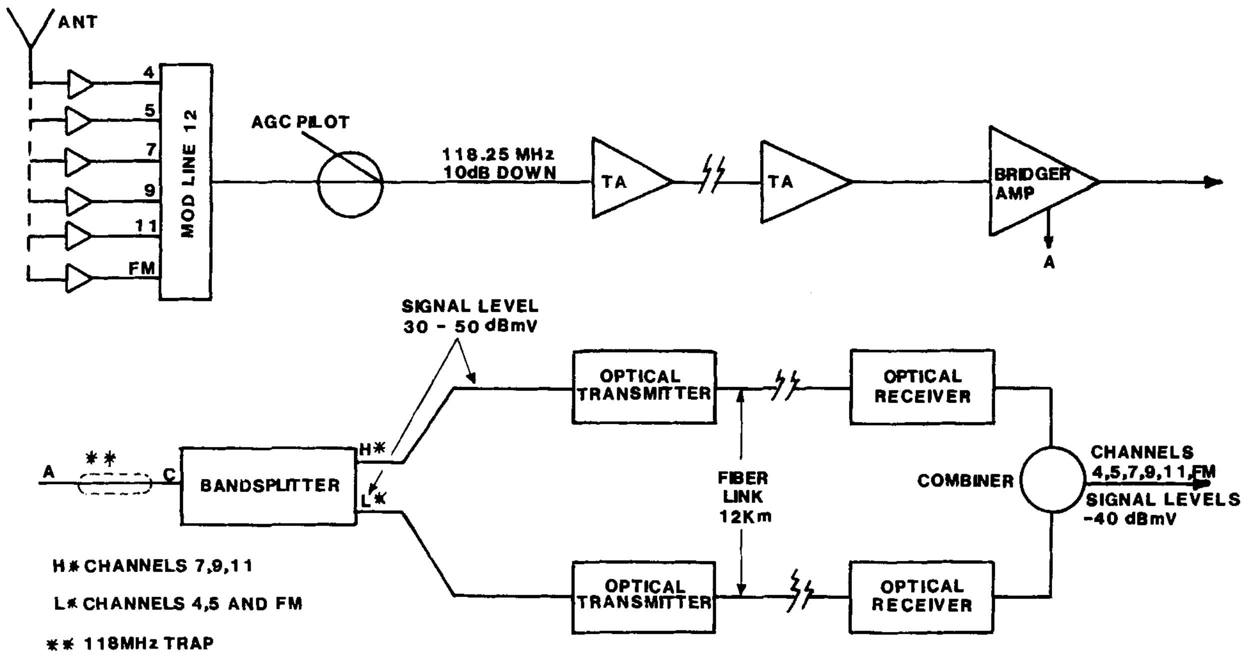
The key performance parameters for these VSB/AM FO systems are carrier/noise and intermodulation distortion. Figure 8 illustrates the typical performance obtained from these VSB/AM FO links. Four carriers at channels 8, 9, 11, and 12 were used for a proof of performance of the links. Carrier/noise (BW=4MHz) per channel measured greater than 45 dB. Third order (worst case) intermodulation distortion measured lower than -60dB. Second order distortion contraints were avoided by choosing each link to transmit less than an octave of bandwidth. Second order distortion measured approximately (40 - 45) dB.

These results represent the current capability of multi-channel VSB/AM FO systems. The lasers used in these FO links are General Optronics high performance Dip 6300 semiconductor laser diodes which have been carefully specified and screened for optimum performance in analog FO systems.

Since the number of VSB/AM channels must be limited (4 - 8) to maintain good performance, these links presently will not accommodate CATV link requirements where channel loadings of 30-50 channels are standard. However, an attractive application for these FO links would be the transport of video in the university or industrial campus environments. FO links are already providing transportation of voice and data in these environments. If multi-channel video distribution is also required, using the same fiber cable (different fibers) for video could result is measurable cost savings.

## POTENTIAL ADVANCES IN VSB/AM FO SYSTEMS

As mentioned earlier, the number of channels which may be transmitted as VSB/AM on a fiber link is currently limited to (4-8) channels depending on the performance objectives. Currently General Optronics has undertaken a study to further improve the performance and increase the number of channels. For this to happen, the key system performance parameters (carrier/ noise and distortion) must be further improved. The following discussions review these FO parameters and suggest how they may be further optimized.




**SEATTLE CITY POWER & LIGHT SYSTEM BLOCK DIAGRAM**

**FIG. 7**

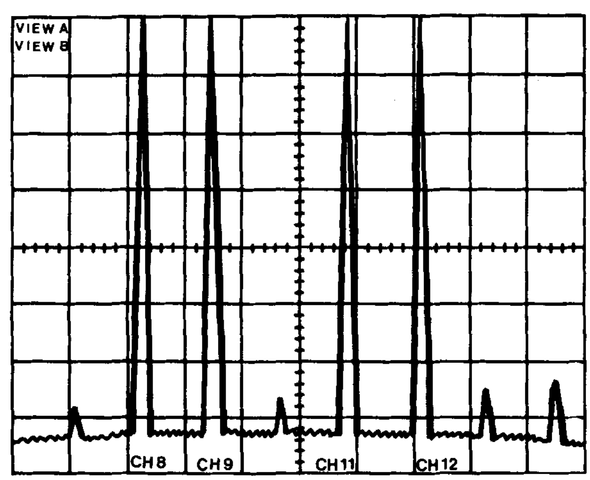
Carrier/Noise

Carrier/noise available at the output of a multi-channel analog FO link (pin-diode optical receiver) is described by:

$$\frac{C}{N} = \frac{(1/2N)(m\,Ro\,Pb)^2}{\underbrace{(RIN\,Ro^2Pb^2B)}_{\text{(SOURCE)}}+\underbrace{2q(Ro\,Pb+Id)B}_{\text{(QUANTUM)}}+\underbrace{(4KTB/Req)Ft}_{\text{(RECEIVER)}}} \quad (2)$$

Ro = diode responsivity (A/W)
m = modulation depth
Pb = average optical power rec'd (W)
q = electron charge
K = Boltzmann's constant
Id = diode dark current (A)
B = bandwidth of receiver (Hz)
T = temperature ( K)
Req = equivalent resistance of photodiode load and amplifier (OHMs)
Ft = noise factor of preamplifier
RIN = source relative intensity noise (dB/Hz)
N = number of FDM channels

As seen from the equation, there are three independent sources of noise present in a FO system: 1) source, 2) quantum, and 3) receiver. Source noise is the inherent residual noise of the laser diode which is referred to as RIN (residual intensity noise). RIN of semi-conductor lasers used for these applications is approximately -120 to -140 dB/Hz. Quantum noise is the "shot noise" of the pin-diode which is directly proportional to average optical power received and bandwidth. Receiver noise consists of the "KTB" noise power of the receiver and the noise figure of the pre-amplifier electronics.




| | | | |
|---|---|---|---|
| CF: | 195 MHz | BIAS: | 33.1 ma |
| HORIZ: | 5 MHz/div | OPTICAL POWER: | 500 uw |
| VERT: | 10 dB/div | MOD. DEPTH: | 60% |
| RES B.W.: | 10 KHz | CARRIER F: | CHANNELS 8,9,11,12 |

**VSB/AM FO LINK PERFORMANCE**

**FIG. 8**

As can be seen from the equation, the carrier/noise versus optical power received (loss budget) will have several breakpoints.

When the optical power incident on the photodiode is low the "receiver" noise term dominants the system noise, so that

$$\frac{C}{N} = \frac{(1/2N)(m\ Ro\ Pb)^2}{(4K\ TB/Req)FT} \qquad (3)$$

Here the carrier/noise ratio is directly proportional to the square of the average received optical power. Thus, for each 1 dB change in optical power received, the carrier/noise ratio will change by 2 dB.

For larger optical signals incident on the photodiode, the quantum noise associated with the signal detection process dominates (assuming Id negligible), so that

$$\frac{C}{N} = \frac{(1/2N)(m^2 Ro\ Pb)}{(2qB)} \qquad (4)$$

Since the carrier/noise ratio in this case is independent of circuit noise, it represents the fundamental or quantum limit for analog receiver sensitivity. In this optical power range the carrier/noise ratio will change 1 dB for each 1 dB change in received optical power.

For very high optical power levels the carrier/noise ratio will be limited by the laser source.

$$\frac{C}{N} = \frac{(1/2N)(m^2)}{(RIN\ B)} \qquad (5)$$

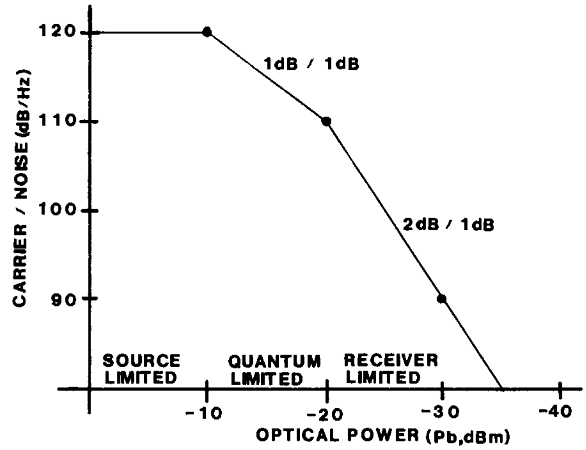
Thus, for very high optical powers, the carrier/noise ratio is constant at the maximum obtainable from the laser transmitter.

Fig. 9 illustrates the carrier/noise obtainable at the receiver output as a function of optical input power when these noise sources are present.

Several conclusions can be from Fig. 9.

1. The ultimate carrier/noise is limited at approximately -10 dBm of received optical power. Thus, for FO loss budgets of 7 dB (10-14 Km), the carrier/noise will be limited by the optical source.

2. The quantum limit will not be achieved due to the RIN noise of the laser.




**CARRIER/NOISE VERSUS RECEIVED OPTICAL POWER**

**FIG. 9**

3. Between -10 to -20 dBm (quantum limited), the carrier/noise ratio will vary 1 dB/1 dB of optical received power.

4. Beyond -20 dBm the carrier to noise ratio degrades 2 dB/1 dB of received optical power.

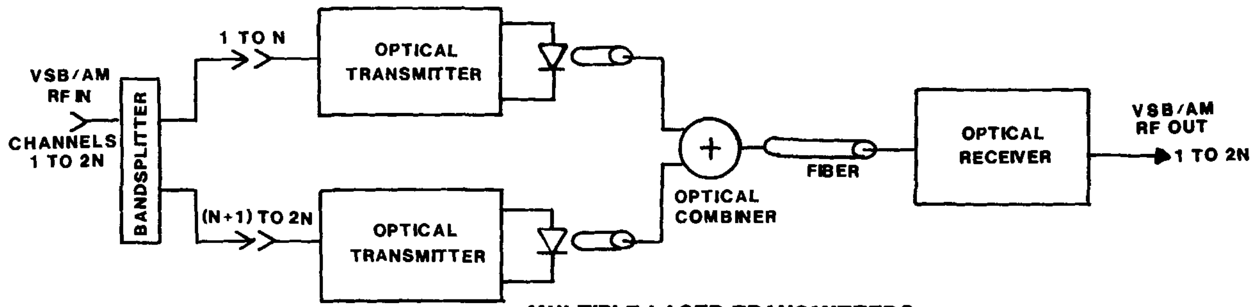
Having reviewed the carrier/noise expression, what options are available to further optimize VSB/AM FO link performance for carrier/noise? The primary candidates are to reduce the RIN of the laser diodes and to increase the modulation index.

For typical lasers emitting several mw of optical power, the RIN lies between -120 to -140 dB/Hz. However, the RIN of the laser is not constant. It depends on the optical power level to which the laser is biased. The RIN varies as the inverse cube of the bias optical power. General Optronics has provided single mode laser diodes which launch optical output powers up to 2.5 mw peak. This can provide up to 10 dB of carrier/noise improvement as compared to 1 mw lasers.

Increasing the modulation depth will also provide a carrier/noise improvement. As "m" is increased by a factor of 2, the carrier/noise ratio will improve by a factor of 4 (6 dB). However, as discussed earlier, laser distortions usually dictate the maximum modulation depth to which the laser is modulated.

Distortion

Augmenting the finite linearity of the semiconductor laser is the key to significant performance improvements.




MULTIPLE LASER TRANSMITTERS

FIG. 10

The benefits of improved linearity are:

1. Higher values of modulation index may be used to drive the laser (thus improving system carrier/ noise ratios).

2. More VSB/AM channels may be transmitted on the FO link without being limited by second and third order distortions.

There are several approaches that provide linearity enhancements in analog FO systems. Since the lasers are the limiting distortion component, all these techniques center about the optical source.

## Multiple Laser Transmitters

This approach is illustrated in Fig. 10. Two laser transmitters are used to double the channels transmitted onto a single fiber and into a single optical receiver. The RF VSB/AM input signals are FDM (frequency division multiplexed) which allows a simple optical combiner to couple the two laser light signals together. If the RF inputs were at the same frequencies, then two distinct laser wavelengths and a wavelength division multiplexer would be required to combine the two laser signals onto a single fiber.

This approach allows a doubling of the number of VSB/AM channels transmitted with the tradeoff of a 3-4 dB loss in the optical loss budget due to the optical combiner.

There are two optical sources required in this approach. However, the costs of lasers are decreasing as a result of competition and product manufacturing maturity.

The RF input signals need to be filtered off and isolated from each other prior to driving each laser transmitter. This may be accomplished with bandsplitting filters.

## Linearized Optical Transmitters

There are two basic approaches which provide linearization of optical transmitters; 1) feedforward compensation and 2) negative feedback.

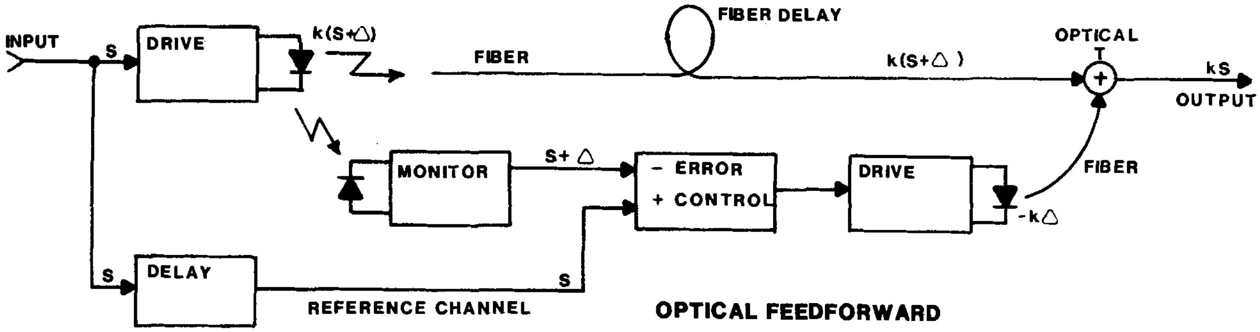
## Feedforward Compensation

Feedforward compensation is achieved by isolating the distortion produced in a nonlinear circuit and subsequently injecting the processed error signal back into the circuit. This is the same principle utilized in CATV RF feedforward amplifiers.

The optical feedforward system shown in Fig. 11 requires a monitoring photodiode, an error processing circuit, and a second optical source to generate a compensating optical signal. This signal is then coupled to the original optical signal through an optical combiner. The practical feasibility of this technique has been enhanced by the development of low loss single fiber optical couplers and combiners.

Optically matched sources must be available to provide significant distortion improvements (20 -30 dB). However, these may be provided by matching LI curves closely. Long term tracking may be a problem if the laser characteristics do not age uniformly. Further investigation in this area is warranted.

Quasi-feedforward compensation (Fig. 12) combines elements of feedforward and predistortion techniques. The incoming signal S modulates two matched optical sources, both of which generate an equal amount of distortion . With the aid of the reference signal path, the distortion from optical source "1" is isolated, inverted and brought to the level required to create a compensating signal equal in amplitude and opposite in sign to the distortion generated by optical source "2". Compensation is achieved by predistortion of the modulation signal S to S-$\Delta$. By accurate error leveling and proper control



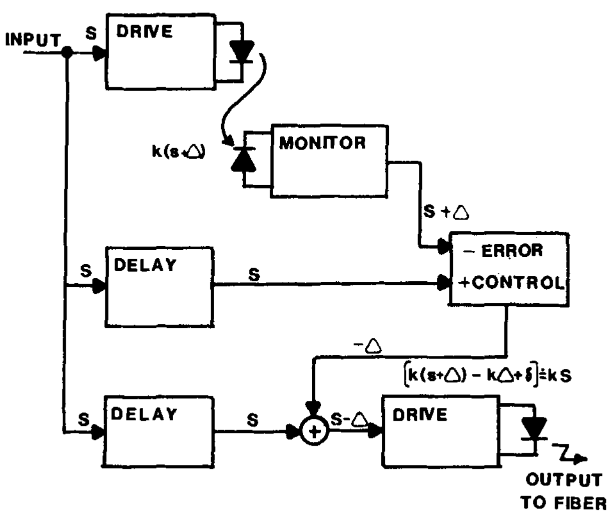

**OPTICAL FEEDFORWARD**

**FIG. 11**

of delays, distortion may be cancelled across a wide range of modulation levels. Second order distortions have been reduced by 35 dB and third orders distortions by 20 dB utilizing this technique.

<u>Negative Feedback</u>

Negative feedback (Fig. 13) relies on a photodiode to monitor the optical signal and provide the necessary feedback signal. The amount of distortion compensation depends on the feedback gain. Although the application of negative feedback is straightforward, large bandwidth requirements may create problems at high frequencies. The utmost available feedback bandwidth depends on the component bandwidths and the time delay caused by the finite length of the feedback loop. This suggests the feedback circuits need to be integrated into the laser package for optimum performance.

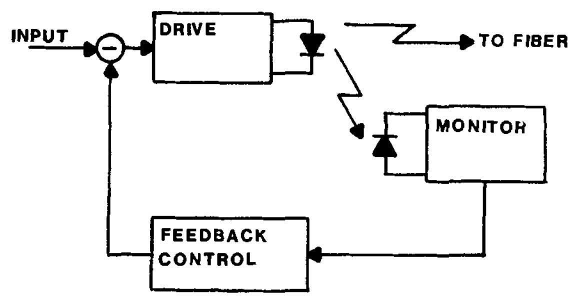



**OPTICAL QUASI FEEDFORWARD**

**FIG. 12**

Negative feedback is preferred over feedforward as a linearization approach because it eliminates the requirement to have matched sources and the cost of two optical sources.

Computer simulations have indicated the capability of achieving 20-30dB of feedback distortion reduction over several hundred MHz bandwidths.




**NEGATIVE-FEEDBACK COMPENSATION**

**FIG. 13**

<u>SUMMARY</u>

Multi-channel VSB/AM fiber optic links have provided good performance for transmission of (4-8) channels per fiber. To provide CATV performance for 30 or more VSB/AM channels per fiber requires selection of lasers for analog applications and development of linearization circuits for the optical transmitter.

General Optronics has already implemented several analog VSB/AM FO systems which have provided CATV performance for up to 12 TV channels/fiber.

Further investigation into linearization techniques are presently underway to further maximize the performance and the number of VSB/AM channels which can be transmitted on a fiber system.