Lightwave Multi-channel AM-VSB Video Systems: Technology Trends and Limits

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ABSTRACT

AM-VSB lightwave technology has advanced rapidly to meet the requirements of the CATV industry. This paper discusses the present state and projected progress of the most promising of many evolving technologies. Presently available fiber systems, based on 1.3 μm wavelength DFB lasers, can be implemented today with considerable cost and performance improvements over coaxial cable. These systems offer performance approaching fundamental limits and, with continued modest increases in output power (3 dB), offer opportunities for limited (4 way) splitting. Externally-modulated YAG lasers could offer similar capabilities, but have not yet been commercialized. Fiber amplifiers offer a possibility for increasing systems margins to the extent required for large scale ($>$ 16 way) splitting, but serious technical hurdles must be overcome. Implementation of such future possibilities would follow naturally from an established base of today's fiber technology.

1. Introduction

With the recent availability of high-performance DFB lasers and the promise of high-power diode-pumped YAG lasers modulated with linearized external modulators, lightwave technology is beginning to make radical changes in the technology base of the CATV network. The ultimate form of this new capability is not yet clear. Advances in system performance have been rapid over the past two years. Laboratory demonstrations of linear optical amplification using Erbium-doped fiber amplifiers (EDFAs) may open the way for passively-divided fiber networks. The system designer is now faced with the choice between implementing currently-available components and waiting for even better future technology. Unfortunately, no-one

can be certain of how each of these technologies will progress.

Although one is tempted to wait and watch the competing technologies evolve, the evolution of each must be driven by a real market. Continued improvements are a certainty, but new systems and rebuilds designed using today's lightwave technology offer significant opportunity for reduced cost and improved performance as well as a platform for tomorrow's services. These advantages can be realized now, and should supercede fears of today's technology becoming obsolete. With linearity close to fundamental limits and numerous vendors emerging with comparable state-of-the-art capabilities, the emergence of a new panacea is unlikely.

In this paper we present an overall perspective on the feasibility and merit of the numerous technology options. We show that although advances will continue within each technology, these advances will be incremental. Optical power levels could continue to increase and noise powers decrease, resulting in modest ($<$ 3 dB) improvements over each of the next few years. Technology breakthroughs realized over the past two years have cleared a path for lightwave CATV, but continued improvements require optimization ($<$ 3 dB), not revolution ($>$ 10 dB). This optimization requires extensive engineering, which must be driven by a volume market. Widespread acceptance of lightwave technology makes sense today and is necessary to drive further improvements.

2. Fundamental Limits

In order to scrutinize claims from aggressive players in a highly competitive market, one would benefit from clearly defined bounds on what is and what is not technically feasible. Unfortunately, although such bounds have been defined, feasibility,

at least among the key competitors, must be qualified by device yield or system reliability. These proprietary intangibles cannot be clarified merely by screening for fundamental feasibility. Nevertheless, the fundamental limits play a crucial role in understanding the overall status of the technology. Noise performance within a few dB of the quantum limit and modulation depths approaching the clipping limit suggest "state-of-the-art" performance. If such systems can be delivered with acceptable prices and in large volumes, then one can assume that the supplier has satisfactory control of the proprietary intangibles. One can then install a "state-of-the-art" system with confidence knowing that a technology breakthrough will not render it obsolete. Two fundamental bounds have been defined; the quantum (shot noise) limit[1] and the clipping limit.[2] Shot noise is generated whenever current flows in a diode and limits the carrier-to-noise ratio (CNR) in accordance with:

$$CNR_o = \frac{I_o m^2}{4qB},\qquad(1)$$

where I_o is the total (average) received photocurrent, m is the modulation depth per channel, q the electronic charge and B is the noise bandwidth of the channel (4 MHz).

Clipping limits the allowed modulation depth for systems using direct or external modulation. This limit exists even if one assumes that the light-versus-current (L-I) characteristics, for a directly modulated laser, or light-versus-voltage (L-V), for external modulators, are perfectly linear within a limited operating range. Infrequent excursions of the modulation current, for a directly-modulated laser, beyond this operating range (clipping) results in a total interference that can be described by:

$$CIR = \sqrt{2\pi}\ \frac{(1 + 6\mu^2)}{\mu^3}\ e^{\frac{1}{2\mu^2}},\qquad(2)$$

where

$$\mu = m\sqrt{N/2}.\qquad(3)$$

N is the total number of channels. Eqn. (2) predicts the total interference from all orders of distortion, which is approximately the sum of all second- and third-order products within each channel. However, since clipping results in a rapid increase in higher-order distortions, the sum of the composite second order (CSO) and composite triple beat (CTB) will generally be less than this CIR. For external modulators one must divide the right-hand side of Eqn. (2) by a factor of two, to account for clipping at both zero and maximum light intensity.

These fundamental limits are plotted in Figure 1, for direct modulation and various values of m, I_o and N. The 3dB reduction of the clipping limit for external modulators makes little practical difference, because of the steep slope of the clipping curves.
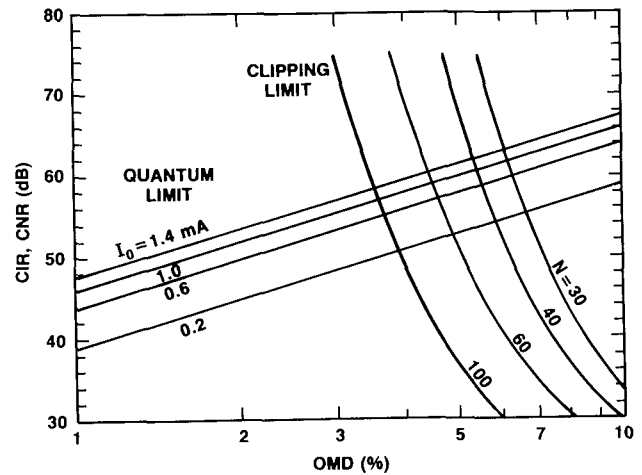

FIGURE 1

Fundamental limits of Carrier-to-noise ratio (CNR) (solid) and carrier-to-interference ratio (CIR) (broken) as a function of modulation depth per channel, for different received currents and number of channels.

State-of-the-art systems have receiver noise and laser relative intensity noise (RIN) contributions such that the CNR is within a few dB of the quantum limit. High performance DFB lasers can be operated with modulation depths very close to the clipping limit. Linearized external

modulators, although not commercialized at this time, have been demonstrated[3] with modulation depths approaching that of the DFBs. For both types of systems, further improvements in linearity, RIN, or receiver design will have little impact. The only unbounded parameter is the transmitted power, which translates directly into additional span or source sharing. Thus the continued improvement in system capability will be realized almost entirely from optimization for transmitted power. This priority is discussed in detail in each of the following sections.

3. Direct Modulation

Systems using directly-modulated lasers are, at this time, the only proven and available commercial alternative. Impairments such as nonlinearity and RIN have been under investigation for years for digital and subcarrier applications. Rapid reduction of these impairments has been possible since no real shift in emphasis in device fabrication has been required. Increased linearity and decreased RIN are both consequences of high output power, and high output power has always been a priority in the development of lasers for all types of systems. The recently available high-performance lasers are the product of this continued development for high power, combined with added motivation and a few special considerations.

3.1 Current Confinement

The key to high-power operation, hence high linearity and low RIN, is in fabrication of a laser structure that effectively confines the injected current to the active layer. The active layer is the small region (2 μm X 0.2 μm) into which electrons and holes are injected from the surrounding p- and n-doped layers of the laser diode. Stimulated recombination of these electrons and holes provides an output optical power that is an extremely linear function of the current injected into the actual active layer. However, not all of the current injected into

the device goes into the active layer. Leakage current, or current that is shunted through the semiconductor material adjacent to this active layer, as shown schematically in Figure 2,[4] reduces the fraction of the total current that is injected into the active layer. The net result is a sub-linear light-versus-current (L-I) characteristic.
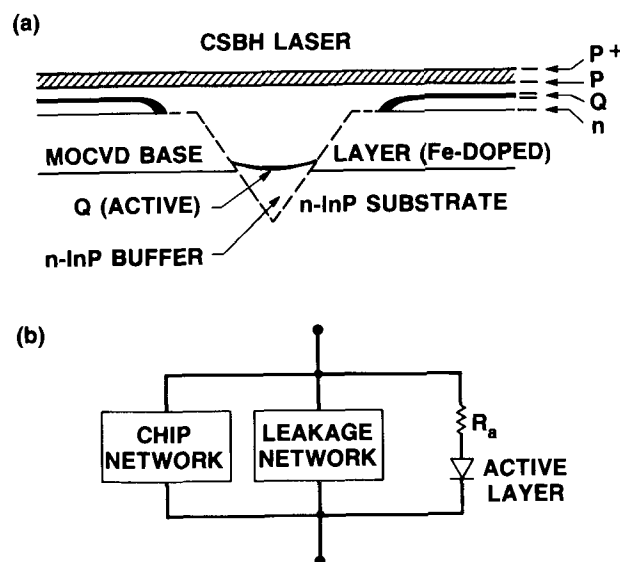
FIGURE 2

Cross section of channel-substrate buried - heterostructure laser (a) showing current through active layer and parallel current leakage path. Circuit model for laser chip (b) showing active layer diode with effective resistance R_a. The leakage network and a chip network amount for imperfection introduced by current leakage and chip parasitics, respectively (from Ref. 4).

Considerable work has been done to reduce leakage current.[5] The laser structure can be modeled, as shown on Figure 2b, by an active layer laser diode in series a small resistance R_a, and two generally problematic networks. Ideally, R_a would be zero and the leakage and chip networks would present infinite impedances. The leakage network generally contains a combination of nonlinear

elements, corresponding to diodes or transistors unintentionally formed by design or fabrication imperfections. Elimination of this leakage, to the degree required for CATV linearity specifications, requires a serious commitment to laser fabrication technology.

The chip network includes the total capacitance of the laser chip, and the resistance and inductance of the bond wire through which current is applied. These parasitics are rarely a problem for the bandwidths required for CATV systems.

3.2 Resonance Distortion

In lasers that have been properly designed and fabricated to reduce current leakage, several other nonlinear mechanisms become important.[1] The most important of these is resonance distortion (RD). RD is a result of the nonlinear coupling between injected carriers and photons, in the active layer of the laser. This is the same nonlinear coupling that results in the relaxation resonance in the frequency response of the laser. For second-harmonic distortion, RD reaches a maximum when the modulation frequency is half the relaxation resonance frequency (f_r). The magnitude of sum or difference product generated by RD is maximum when the sum or difference frequency is equal to f_r. For third-order distortion, RD has maxima whenever combinations of two or three of the participating frequencies equal f_r. Fortunately, RD is zero at zero frequency and f_r is generally greater than 5 GHz, for good lasers. It is important to note that, although modulation bandwidths (resonance frequencies) need not exceed 500 MHz for signal response, f_r must be greater than approximately 6 GHz to eliminate unacceptable levels of RD.

3.3 Longitudinal Mode Control

The best system performance is obtained using single-frequency distributed feedback (DFB) lasers. These lasers use a Bragg grating along the length of the active layer to suppress laser oscillation at all but one optical frequency. Fabry-Perot (FP) lasers, which are much more easily fabricated, oscillate because of feedback from optical reflections at the cleaved ends of the active layer. Hence FP lasers oscillate in several (10) closely spaced (typically 1 nm separation) longitudinal modes of the FP resonator cavity. Power in each of these modes fluctuates randomly such that the total output power is constant. However, since fiber dispersion causes each mode to travel through the fiber with a different velocity, the power received after several kilometers of fiber fluctuates randomly. The resultant intensity noise makes FP lasers unacceptable for high-performance CATV systems utilizing AM modulation techniques. Properly fabricated DFB lasers operate in only one longitudinal mode. Mode-partition-induced intensity noise is therefore not a problem.

3.4. 1.3 Versus 1.55 μm Wavelength

The high-performance DFB lasers that are currently available meet the linearity and noise requirements as a result of considerable effort on the part of committed laser manufacturers. As of this date, this effort has been focussed on devices that operate at a wavelength of 1.31 μm, where the fiber loss is near 0.4 dB/km. Operation at 1.55 μm, where the fiber loss is typically 0.22 dB/km, has been demonstrated.[6] At this time it has not been determined whether the reduced fiber loss at 1.55 μm can make up for an intrinsic reduction in laser output power.

This reduction has two sources. The efficiency of current-light conversion is reduced by several mechanisms that consume injected carriers without creating photons.[5] One such process is Auger recombination, the effect of which increases rapidly with increasing wavelength. The second source of reduced efficiency at 1.55 μm is coupling into the fiber. Typical coupling efficiencies at 1.55 μm are 0.5 to 1.0 dB smaller than at 1.3 μm.

By far the most convincing argument for 1.55 μm laser development is for compatibility with Erbium-doped fiber amplifiers, as discussed in Section 5. These amplifiers may develop into essential components for future systems, but this is not certain. If they do, then committed 1.55 μm laser development will be required.

4. External Modulation

Recently available YAG lasers, pumped with high-power GaAs laser diode arrays, are capable of output powers in the vicinity of 200 mW. Unfortunately, dynamics within the YAG material make it impossible to modulate the output power, at frequencies required for CATV, by directly modulating the pump intensity. External modulators are essential. Unfortunately, external modulators have two serious problems; high insertion loss and poor linearity. Overcoming these problems has proven difficult, and although laboratory demonstrations have been successful, a commercially viable YAG-laser-based CATV system is not yet available.

Of the many types of modulators proposed, $LiNbO_3$ modulators are the only choice for CATV purposes. With proper attention to fabrication detail, these devices can be sufficiently stable and capable of handling YAG optical power levels. The insertion loss comes from several sources. Since the performance of the modulator depends on the state of polarization of the input light, polarization-preserving fiber is generally used to couple into the modulator. Efficient coupling from the laser into this fiber is more difficult than coupling into standard fiber. Power is also lost coupling from fiber into and out of $LiNbO_3$ waveguides and from waveguide bends that form the modulator. The total fiber-to-fiber insertion loss of a very good device is near 3 dB. Also, the device must be biased at a voltage corresponding to 50% transmission, at which point the linear intensity modulation is most linear. Combining these losses reduces the total coupling efficiency, between the laser and the output of the

modulator, by at least 8 dB. Of the 23 dBm available power, approximately 15 dBm could be expected, at best, to be coupled into the output fiber. Reported values are somewhat less.[3,7]

Although this power level is higher than all but the best DFB lasers,[8] linearity must also be considered. $LiNbO_3$ transfer characteristics are intrinsically nonlinear. This nonlinearity arises because of the interferometric conversion of a relative phase difference into intensity (For Mach-Zehnder interferometer modulators). If biased at the point of inflection in the L-V curve (50% transmission) the second-order distortion is small, but the third-order distortion is approximately 30 dB worse than for directly-modulated lasers.[9] Without a linearization technique, the modulation depth per channel must be limited to less than 2%, which is less than half that used for direct modulation. The corresponding reduction in signal power generally eliminates any advantage that could have been gained by the high power and low noise of the YAG laser.

Linearization techniques change this state entirely, but are difficult to implement. Successful demonstrations have been reported[3] with modulation depths near 3.3%, for a 42 channel load. However, complications like poor coupling, noise from the linearizer,[3] or inadequate drive power for the modulator[10] always prevent externally-modulated systems from performing with the high power and low noise levels theoretically possible from the YAG lasers. Also, the reliability of the diode pump lasers has not yet been proven. These factors, combined with difficulties in manufacturing and packaging, has limited the commercial success of externally-modulated systems.

5. Optical Amplifiers

It is hoped that optical amplifiers can be used to improve the limited loss margins available from lightwave technology, making it possible to passively divide the optical signal between many fibers. Recent

experiments[11,12,13,14] have demonstrated such possibilities, but many unknowns remain. Problems arise because of the high optical power levels required for high CNR. A lightwave CATV receiver must receive more than 0.5 mW of optical power. Unfortunately, the saturated output power for most types of optical amplifiers, defined by the output power for which the gain is reduced by 3 dB (optical), is typically less than 10 mW. In order to get reasonable increases in system margin, the amplifier must be operated in deep saturation. This generally results in increased noise and distortion.

Three types of optical amplifiers could be considered for CATV applications. Bulk semiconductor traveling-wave amplifiers are fabricated by removing (using anti-reflection coatings) the reflecting facets on Fabry-Perot lasers. This leaves a gain region in which the power grows exponentially as the optical signal propagates along the device. These devices have saturated output powers of several mW and can operate at any wavelength. The problem with these devices is nonlinearity. Gain is provided by stimulated recombination of electron-hole pairs. If the optical input signal is modulated, then the rate at which carriers are consumed is modulated, resulting in a modulated gain. The optical output is then a product of the modulated input and the modulated gain, which results in a nonlinear mixing. This nonlinearity is especially bad when the amplifier is close to saturation.

Much higher saturated output powers are available from multiple-quantum-well (MQW) semiconductor amplifiers. These devices are similar to the bulk amplifiers described above, except that the gain layer is replaced by several extremely thin layers (100 Å). Injected carriers are confined to discrete quantum states within each layer, such that stimulated electron-hole recombination occurs over a narrow frequency range, compared to bulk amplifiers. Saturated output powers near 50 mW have been measured.[15] Although these amplifiers suffer from the same nonlinear processes as described above, they could be

operated well below saturation. The resulting distortion could be small, but this remains to be determined. These devices are strictly in the research phase and are not considered as near term possibilities. At present there is no alternative for CATV-compatible optical amplification at the 1.3 μm wavelength.

The most promise for CATV-compatible amplifiers is with Erbium-doped fiber amplifiers (EDFAs). EDFAs are fabricated using the same processes as standard fibers, but the core is doped with a high concentration of Erbium. Light from high-power pump lasers, at wavelengths of 0.98 μm or 1.48 μm, excites Erbium ions into an upper state. This upper state decays rapidly to an intermediate state, at which the ion remains awaiting stimulated or spontaneous decay. Decay stimulated by an input optical signal provides gain. The wavelength corresponding to this final transition is near 1.55 μm. Other dopants may provide optical gain at wavelengths near 1.3 μm.

Although EDFA-amplified CATV systems have been demonstrated, many unanswered questions remain. Characterization of the linearity is difficult since few linear DFB lasers exist at 1.55 μm. Noise characteristics depend strongly on the power and frequency of the pump lasers. Nevertheless, an amplified 1.55 μm 42 channel signal, from a DFB laser, has been amplified and split 16 ways,[13] with a CNR of 50 dB and composite distortions better than 60 dB. This demonstration suggests that these amplified systems will eventually be available.

The experiment used to demonstrate the 16 way split is shown in Figure 3. The EDFA consists of 45 meters of EDF, 2 high-power 1.48 μm semiconductor pump lasers, 2 wavelength multiplexing couplers, and several optical isolators. Each pump laser supplies 25 mW of optical power to the amplifier. The reliability of pump lasers operated at these power levels must be investigated thoroughly. This pump power results in a saturated output power of 6 dBm. The couplers allow the 1.48 μm pump light to be combined with the 1.53 μm source

laser with little loss. Isolators are required because the EDFA, like all optical amplifiers, provides gain in both directions. Without the isolators, reflections from fiber connections can produce frequency dependence in the gain, or even laser oscillation.
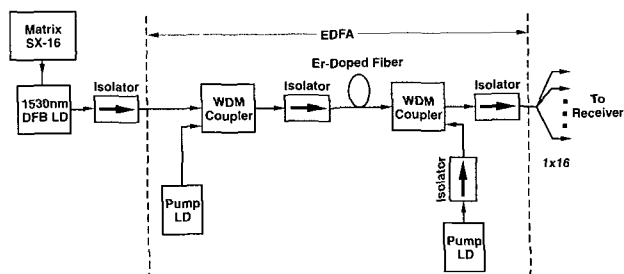

FIGURE 3

Schematic for 16-way split using Erbium-doped fiber amplifier (from Ref. 13).

By operating the amplifier well into saturation, a total output power of 12.2 dBm was achieved. The unsaturated gain of more than 30 dB was then reduced to less than 20 dB. Although this apparently caused little nonlinear distortion, the noise figure for the EDFA was 11 dB, which is much worse than generally obtained for unsaturated operating conditions. Getting an adequate CNR with such high noise figures requires an excessively high modulation index, and input signal powers greater than 1 mW,[16] hence placing further burden on the design of good 1.55 μm DFB lasers.

To summarize the status of EDFAs for CATV applications, it is apparent that the technology can be made to work, but the noise performance is questionable. For future systems, in which a high CNR must be delivered, noise from just a single EDFA may be unacceptable. The reliability of the pump lasers, operated at high power levels, and the optimum pump wavelength need to be clarified. Linearity does not appear to be a problem, but the nonlinear mechanisms have not been investigated thoroughly. The feasibility of such systems also hinges on the availability of linear low-noise 1.55 μm

source lasers.

EDFAs may be an integral part of the future CATV network, but they do not obviate enthusiasm for currently available 1.3 μm technology. The cost of each amplifier, given the component count shown in Figure 3, is likely to be attractive only if a high degree of splitting (> 8) is possible. The additional noise introduced by the amplifier may hinder the high CNR (55 db) desired in upgraded trunk systems. Implementing a network based on 8 or 16-way fiber splitting requires design flexibility that does not exist in established systems. Upgrading existing systems may require the flexibility and incremental growth offered by the 1.3 μm systems, which offer limited splitting opportunities (2 or 4 way). Improvements will also continue with these 1.3 μm systems, including the possibility of 1.3 μm fiber amplifiers. One must compare the cost of the amplified system with that of systems based on future high-power DFB lasers. Introduction of whatever future technologies become available will be simplified if an established base of existing lightwave technology is in place.

6. Fiber/System Impairments

Optical fibers are as close to being a perfect transmission media as could be expected. The low loss, high bandwidth, immunity to electromagnetic interference, material stability and high strength have driven the explosive growth of digital fiber systems. For CATV applications, the only problems arise from reflections and Rayleigh backscatter. Dispersion is a problem if multi-longitudinal-mode sources are used, but not for DFB or YAG lasers operated at wavelengths close to the dispersion minimum. Dispersion can also introduce nonlinear distortion, for lasers operated far from the dispersion minimum.[14,17] Optical power levels are not near the magnitude at which fiber nonlinearity becomes a problem.

Fiber reflections, if coupled back into the laser, increase the intensity noise and nonlinear distortion generated by the laser.

Any high-performance system available today uses an optical isolator to eliminate this problem. At least 30 dB isolation is needed to remove feedback problems in systems that have been carefully installed so as to minimize reflections.

Another problem with backscatter and reflections is that the direct signal mixes with delayed reflected signals on the photodetector. The photocurrent generated by the detector is proportional to the square of the total optical field. This generates a beat product between the direct and reflected signal that can generally be described by an effective intensity noise. The amount of noise generated in the CATV band depends on the optical spectrum of the modulated source. Measured source spectra[1] suggest that two fiber reflections of -30 dB (optical power) can limit the CNR to 57 dB. Since one can anticipate reflections from many connectors within the system, reflections from each must be considerably less than -30 dB. Other reports[15] indicate that the intrinsic Rayleigh backscatter of the fiber may produce effective relative intensity noise levels of -150 to -160 dB/Hz. This noise, which may be higher than that generated by the laser, is intrinsic in that the light attenuated by the fiber is scattered by microscopic refractive index variations in the fiber.

7. Conclusions

AM-VSB lightwave systems have been developed that meet the cost and performance required for widespread application within the CATV industry. This capability is the result of rapid development, over the past two years, of high performance 1.3 μm DFB lasers. These systems offer spans greater that 10 km and limited passive division. Further refinements of this technology will yield incremental improvements only. Hence, obsolescence of today's "state-of-the-art" equipment should not be feared.

Several alternative technologies may emerge within the next few years. Of these, the most significant potential for improvement is offered by fiber optical amplifiers, which may provide sufficient transmission margin for signal division between tens of fibers. Since this splitting capability may not conform to many present trunk topologies, presently available DFB systems should remain in high demand. Widespread implementation of available fiber technology will provide not only the needed improvements in quality and reliability, but a platform on which a future can be built.

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