OPTICAL AMPLIFIERS FOR VIDEO DISTRIBUTION

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ABSTRACT

The promise of a broadband fiber communications network has attracted the interest of CATV and Telco concerns. Various networks and Topologies have been discussed. Cost is a drawback in some of the proposed networks, particularly those networks which require switching. This paper discusses a low cost broadcast tree and branch network which utilizes optical amplifiers to extend the network penetration. Recent work in the development of optical amplifiers suggests that the Erbium fiber amplifier may be compatible with VSB-AM. The characteristics of such an amplifier will be discussed. This scenario allows an orderly transition from present day AM backbone system to the tree and branch fiber architecture. Once the broadband fiber plant is in place new services can be implemented that exploit the broadband nature of fiber.

INTRODUCTION

Optical Amplifiers have been studied for fiber optics since 1973. Significant work has been expended in the last ten years to develop practical devices. The last three years have shown an exponential increase in the development of these components. Most of the major makers of laser diodes have programs to develop semiconductor amplifiers.

The major telecommunications companies have demonstrated that the optical amplifier can be used to increase the link budget in digital applications.[1] During the past two years a number of demonstrations have shown that the link budget in subcarrier FM[2] fiber video systems can be significantly extended via optical amplifiers. These experiments have utilized FM or digital to solve the problems of adequate signal to noise ratio for a large number of channels, as well as for adequate system linearity. The technology has successfully demonstrated that 90 channels of video can be subcarrier multiplexed on a single laser using FM modulation. A sketch of a Bellcore[3] experiment where two optical amplifiers were used to send 90 channels of microwave sub-carrier multiplexed FM modulated video over a tree-and-branch network serving 2,048 subscribers is shown in figure 1. Commercial microwave satellite electronics equipment was used in the testing. The signal-to-noise (SNR) obtained in the referenced 90 channel experiment was 55 dBc. Composite second order (CSO) and composite triple beat distortion (CTB) are not a problem with FM transmission since the amplifier need only be capable of about 20 dBc CSO and CTB for top quality video. These demonstrations are significant since they show that a high quality, high channel capacity, electrically passive, video distribution network can be constructed using fiber. Optical amplifiers have the potential to lower the cost and improve performance in fiber video distribution systems. As volume increases it is likely that the cost of the optical amplifiers will drop. An optical amplifier capable of delivering AM video services would seem to provide the basis for the most cost effective distribution.

Analog Video Loop Distribution Using Two-Stage Cascade Optical Amplifiers

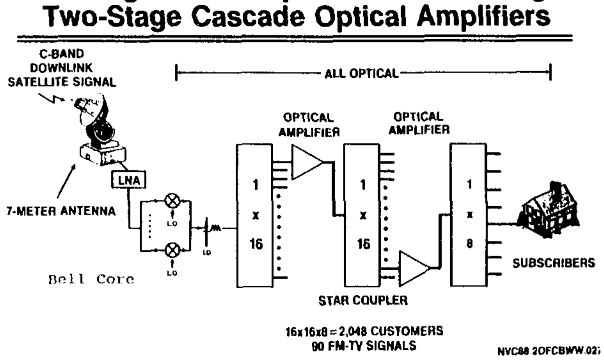

FIGURE 1

The optical amplifier is a designer's dream. The optical semi-conductor amplifier has a gain bandwidth product of about 300 THz, about 100 times that of the best microwave amplifiers. In addition, analysis has shown that optical fiber amplifiers having noise figures of about 3.5 can be realized[4]. Semi-conductor optical amplifiers with noise figures of 5.2 have been realized[5]. The optical amplifier is required to make a tree and branch structure practical for video distribution. It is believed that the tree-and-branch structure can be utilized to implement the fiber backbone or other similar architecture. See figure 2.

BRANCHING FOR AM FIBER BACKBONE

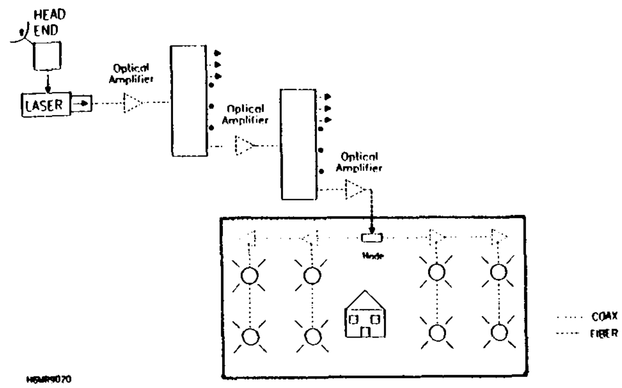

FIGURE 2

The tree and branch structure is needed to reduce the required amount of fiber. This is extremely important since the fiber plant is the most expensive component in the distribution scheme. Fiber is an ideal medium for video transport; it is a low loss medium, and it has a large bandwidth. A fiber tree and branch network will significantly reduce the number of active components between the headend and the subscriber, when compared to present video distribution networks. At present there may be more than forty amplifiers between the headend and the subscriber. The fiber backbone approach can be used to achieve a reduction in the number of cascaded electronic amplifiers. This would be advantageous since the SNR degradation due to amplifier cascade would be greatly reduced. The reduction in the number of active components in the distribution network would also lead to a more reliable network. An additional advantage is that the fiber plant supports virtually unlimited signal bandwidth. This excess bandwidth capacity can be utilized in the future as bandwidth demand grows. The optical amplifier is an inherently simple device with low power consumption. The semi-conductor amplifier is a monolithic component (see figure 3). The fiber amplifier requires an optical pump in the form of a monolithic semi-conductor laser, a fiber coupler for combining the pump and signal beams, the rare-earth doped fiber and possibly optical isolators (see figure 4).

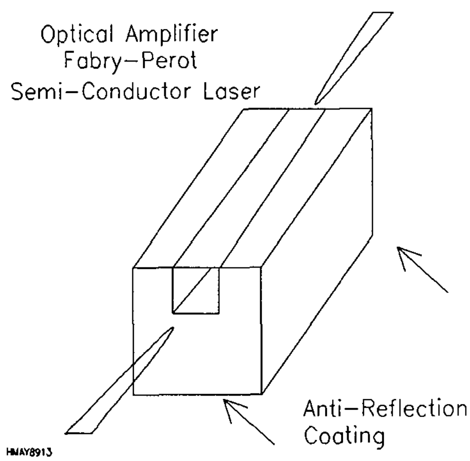

FIGURE 3

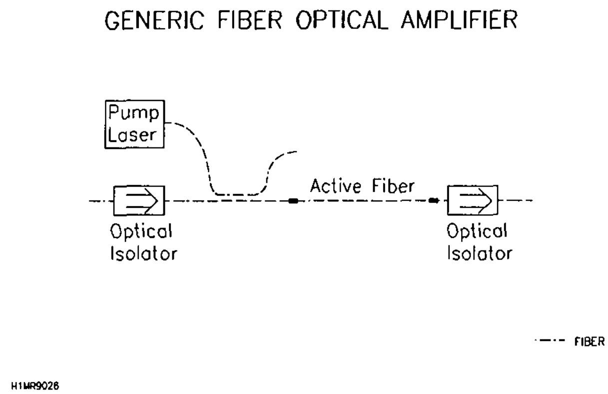

FIGURE 4

The demand for video bandwidth will grow due to increased numbers of broadcast channels, higher channel bandwidth requirements of HDTV and new services such as switched or bidirectional video. Fiber networks with optical amplifiers can transparently support changes in signal bandwidth and modulation format. The most popular modulation and multiplexing formats for fiber transmission are AM, FM, digital pulse code modulation (PCM), optical wavelength division multiplexing (OWDM) and optical frequency division multiplexing (OFDM). OFDM differs from OWDM in that it requires a coherent local oscillator for recovery of the transmitted information. With the exception of high density multi-channel AM, laboratory experiments have demonstrated the compatibility of the optical amplifier with all of the above modulation formats. Tests are under way in laboratories to determine the compatibility of the Erbium fiber amplifier with VSB-AM.

The low noise characteristics of the optical amplifier make it desirable for use as the first gain stage in a conventional high bandwidth fiber optic receiver. The optical amplifier can also be used to construct a fiber optic switch[6]. See figure 5. Recently, four-wave optical mixing has been demonstrated in semi-conductor optical amplifiers[7]. In this case, four-wave mixing was used to transfer the modulation from one optical frequency to that of another optical frequency. Optical frequency exchange could be important for future switched networks that are able to discriminate optical frequency.

OPTICAL AMPLIFIER USED
FOR BIDIRECTIONAL SWITCH

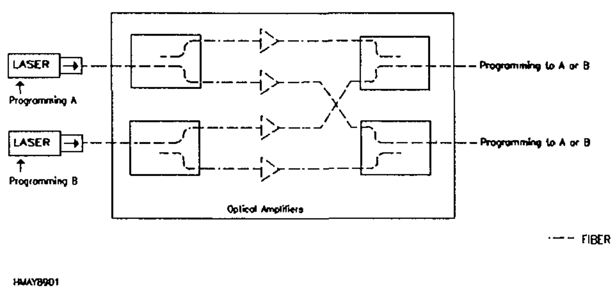

FIGURE 5

Both fiber and semi-conductor optical amplifiers are bi- directional devices, so a bi-directional network is possible in theory. A system architectural analysis of a specific fiber plant would be required for practical bi-directional systems. Reflections and optical noise terms limit practical systems.

In volume, the optical amplifier has the potential for relatively low cost. The compact disk player is the first consumer product to incorporate a laser. The path to lower cost in optical components is found by increasing the installed base of that component.

STRATEGY

The introduction of fiber plant overlay will improve performance, reliability and provide a means of offering new revenue producing services. The introduction of fiber plant may also be required to maintain a competitive posture.

COMMERCIAL MARKET STATUS

Within the last two years a number of vendors have begun offering commercial semi-conductor optical amplifiers. Most of these devices are developmental devices. A few companies are presently qualifying semi-conductor optical amplifiers for undersea telecommunications applications. Laboratory work is underway to develop the Erbium fiber amplifiers for telecommunications and CATV applications. Doped Erbium fiber and semi-conductor amplifiers are the technologies that are viable for near term development.

PENETRATION

Penetration of fiber into the subscriber network will lead to improved system reliability and higher quality video. The first thrust into the network is to deliver video to the node as in the fiber backbone architecture. The optimum placement of the optical amplifiers depends on a number of system parameters, which would be determined by component performance. Figure 2 is an AM network topology that could be supported by optical amplifiers having a modest fiber-to-fiber gain. Optical amplifiers have demonstrated 23 dB gain at a saturation output power level of 20 mW. Amplifiers having this level of performance allow a cost effective network to be built. The next evolutionary step would be to cascade an additional stage of optical amplifiers.

TYPES OF OPTICAL AMPLIFIERS

There are a number of types of optical amplifiers that are compatible with fiber systems. These are shown in figure 6. Earlier in the discussion it was indicated that one great advantage of fiber is that the fiber attenuation is very low. That is the good news. The bad news is that it is difficult to achieve the high signal power necessary for VSB-AM CATV distribution. This is an important point since VSB-AM tree and branch is very desirable so that the cost of distribution may be kept low. Optical amplifiers may aid the distribution of video via the fiber backbone approach.

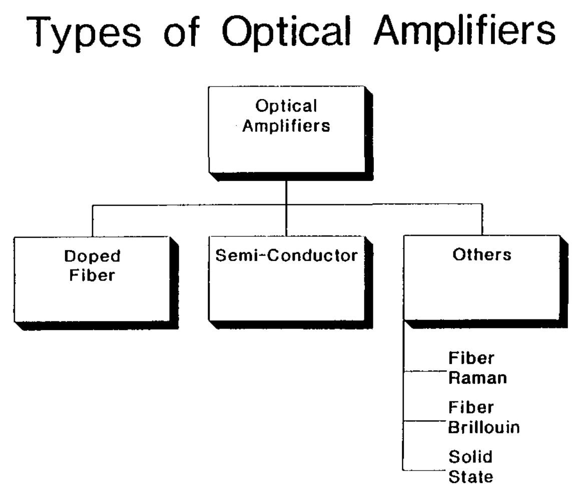

FIGURE 6

Semi-conductor Optical Amplifiers

Most of the semi-conductor optical amplifiers that have been built to date are standard lasers with a precision anti-reflection coating applied to the facets. The anti-reflection coating must be sufficiently good that even residual lasing action is inhibited. The first problem lies in the removal of the mirrors. It is desirable to achieve reflectivity[8] on the order of 10^{-5}. As expected, it is very difficult to achieve these results with multi-layer dielectric coatings. Unfortunately, these devices are produced one at a time by individually monitoring each laser during the coating process. Work is also being done to reduce the stringent requirements placed on the anti-reflectivity coating. The most promising technique is to place the waveguide at an angle relative to the cleaved facet. This technique coupled with a modest anti-reflection coating promises to yield effective facet reflectivity near 10^{-5}. One or the other of these two techniques is required to produce reflectivities on the order of $R=10^{-5}$. Reflectivities this low are required to produce an optical amplifier with high saturation output power. The slanted facet concept coupled with a modest anti-reflectivity coating offers promise for mass production of optical amplifiers.

The material gain peak in some semi-conductor amplifiers is not aligned with the standard communications wavelength. This problem occurs in amplifiers that are based on standard lasers. An increase in threshold current brought on by lowering the facet reflectivity causes a corresponding increase in injection current density, this in turn causes the center of the material gain peak to shift to shorter wavelengths. One way around this problem without changing the material doping or optical cavity is to cleave the amplifier chip at a longer length. A standard laser chip is about 300 um in length. Chips that are destined to become optical amplifiers are cleaved at about 500 um, the device can then be operated at a lower current density, thereby shifting the gain curve peak back toward the standard operating wavelength.

Current devices have polarization sensitive gain. The gain sensitivity to polarization decreases to about 3 dB maximum at a reflectivity near $R=10^{-4}$. Devices with $R=10^{-5}$ exhibit some residual polarization sensitivity which stems from the design of the optical cavity. Paper studies examining the optimization of the gain medium for the optical amplifiers application have been published. Major laboratories have programs to begin producing amplifiers incorporating these ideas as part of their optical amplifier development programs.

A major problem affecting the semi-conductor optical amplifier is the efficiency of the fiber coupling. Current commercial devices have as much as 6 dB loss per facet. This 12 dB loss reduces available gain from 27 dB to 15 dB. The poor input coupling efficiency also increases the noise figure. If the input coupling efficiency were 100%, semi-conductor amplifier noise figures near 3.8 dB could be obtained.

Semi-conductor optical amplifiers are based on mature technology. Relatively slight modifications to the existing Fabry-Perot device structure, an anti-reflection coating and an additional fiber pigtail produces an optical amplifier. The semi-conductor optical amplifier is also directly pumped, leading to a very simple and reliable device. These devices have been commercially developed for undersea applications[9]. It is expected they will be deployed in three years. The limiting factor in undersea deployment is the qualification program which requires three years.

Another problem with semiconductor optical amplifiers is that there is a large optical loss associated with coupling the light from fiber to amplifier and back to the fiber. At present the combined input and output loss for commercial semiconductor optical amplifiers may be as high as 12 dB. Even with this high loss, amplifiers with gains as high as 15 dB can be realized. Recent devices with 3 dB optical saturation powers as high as 45 mW have been achieved. These devices offer a broad 3 dB gain bandwidth. Standard laser structures offer 40 nm bandwidth, while recently developed quantum-well devices may offer 100 nm of optical bandwidth. One drawback of the semiconductor optical amplifier is that the excited state life-time of the optical carriers is short compared to video modulation rates. This leads to large intermodulation distortion products at power levels and subcarrier frequencies that are compatible with VSB-AM. The semiconductor amplifier works well with digital and FM subcarrier modulation.

Brillouin Fiber Amplifier

The Brillouin fiber amplifier utilizes the non-linear properties of standard fiber. In this amplifier, a narrow linewidth pump laser is co-propagated with the signal laser in a fiber. The gain bandwidth of the Brillouin amplifier is about 100 MHz. Gain is present at an optical frequency that is offset by about 11 GHz from the pump laser. Because of the narrow gain profile, the usefulness of this fiber amplifier is limited to special applications. One application is as an all optical phase lock loop for the recovery of a vestigial local oscillator in coherent phase shift keyed systems.

Raman Fiber Amplifier

The Raman fiber amplifier is also made with standard fiber. An incident pump laser photon is scattered to a lower optical frequency by a vibrational state of a silica molecule. Unlike Brillouin gain, the gain bandwidth of the Raman amplifier is 40 THz, with a sharper satellite peak which has a 13 THz bandwidth. The Raman pump power threshold at 1.55 um is 600 mW. At present it is difficult to achieve this level of pump power with semiconductor pump lasers. This amplifier could become important when higher power semiconductor lasers are developed.

Doped Fiber Amplifiers

A functional schematic of a fiber doped amplifier is shown in figure 4. Early work utilized Neodymium (Nd) doping for operation near 1.0 um or 1.3 um. These amplifiers have not found use as practical amplifiers because they suffer from excited state absorption (ESA) of the signal when operated at 1.3 um. In the Nd amplifier ESA of the signal laser is the dominant transition from the excited state. Current interest is centered in Erbium doped silica fibers. This laser system is free from excited state absorption under certain conditions.

Erbium Fiber Amplifier

Erbium fiber amplifier is made by doping a fiber with the rare-earth Erbium. A co-propagating pump laser excites the Erbium laser system. This laser system is shown in figure 7. The excited state lifetime of the $^4I_{13/2}$ line is very long, about 12 mS. This long excited state lifetime yields an amplifier with characteristics that may be compatible with VSB-AM. It is believed that CSO and CTB levels compatible with VSB-AM can be achieved. Erbium fiber amplifiers with gains higher than 40 dB have been demonstrated. Separate experiments have demonstrated amplifiers with output saturation powers higher than 20 mW. The Er doped fiber is a three level laser system that may be pumped at a number of wavelengths. Each of these pumps has attributes which affect its desirability as a pump laser. A number of pump lasers have been considered. A summary of some of the practical considerations follows.

532 nm: This source would be frequency-doubled Nd:YAG. KTP could be the doubling material. The Nd:YAG requires a semi-conductor pump in the area of 800 nm. This could show promise as guided- wave non-linear optics are developed. This is a desirable laboratory wavelength because these components are all available commercially.

807 nm: This is available from high power injection locked GaAlAs diode arrays. Both 532 nm and 807 nm are multimoded in the Er doped fiber so pumping efficiency suffers because of poor mode field overlap between the pump and signal wavelengths. Both the 532 nm and 807 nm pump wave suffer from excited state absorption of the pump.

DOPED FIBER LASER SYSTEMS

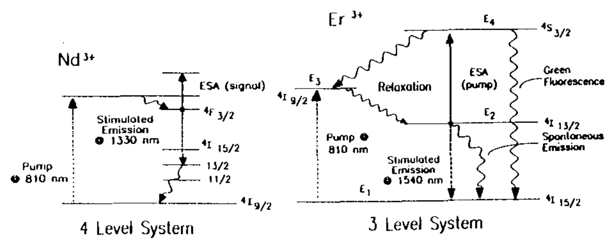

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FIGURE 7

980 nm: Ion pumped dye lasers have demonstrated this pump wavelength. This wavelength is free from excited state absorption. Indium doped GaAs semi-conductor laser operation at 980 nm has been demonstrated in research environments. Development work indicates that high power strain[10,11] layer lasers may produce a reliable high power laser source for use as a commercial pump. The 980 nm pump produces an amplifier with a lower noise figure than the 1480 nm pump and is a more efficient pump.

1480 nm: This is an advanced structure, high power GaInAsP laser diode. This is an attractive pump since there is no excited state amplification and the mode fields of the pump and lasing fields have good overlap. Table 1 compares the efficiencies of these various pump lasers.

One of the advantages of the doped fiber amplifier is that low reflectivity splicing to CATV fibers is easily accomplished. Unfortunately the ideal mode field diameter for a doped fiber amplifier is not the same as for a CATV fiber; however, the mode field is Gaussian so a simple Gaussian transformation in a tapered fiber should lead to a very low loss interface between the amplifier fiber and transmission fiber. There are a number of researchers[12] that are active in developing these transformation devices. High coupling efficiency is required to achieve an optical amplifier with a low noise figure. Fiber amplifiers have been demonstrated to have a saturation power level of 20 mw[13]. Fiber-to-fiber gains of 50 dB have also been reported.

The spontaneous emission spectra of an Erbium fiber amplifier with and without an amplified signal is shown in figures 8 and 9.

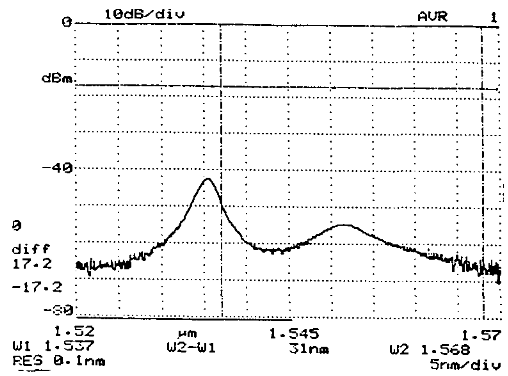
TABLE 1

GAIN PER UNIT OPTICAL PUMP POWER

Pump Wavelength	Gain dB/mW
665 nm	.26
514 nm	.22
528 nm	.31
647 nm	.23
807 nm	.30
980 nm	2.20
1480 nm	.30

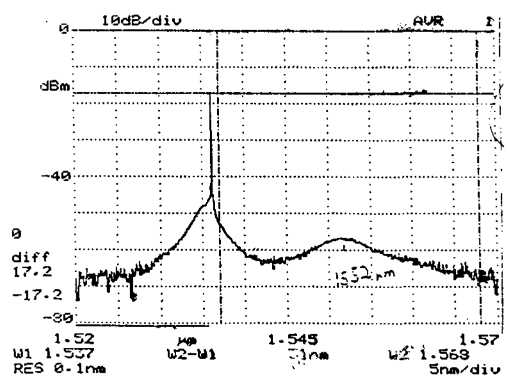
Er Fiber Amplifier

Output of Optical Amplifier Showing Amplified Source



Spontaneous Emission of Erbium Fiber Amplifier

FIGURE 8



Gain dc 19 dB
ac 14 dB

Distortion CTB >57 dB

FIGURE 9

The characterization of amplifier CTB and CSO is extremely important in the transmission of multi-channel analog intensity modulation. Characterization of CTB and CSO is an area that researchers at Jerrold Applied Media Lab are examining. All distortion tests to date have been limited by laser probe performance, not amplifier performance. The following is a summary of the results that have been obtained. Single tone distortion tests have been made that extrapolate to better than 65 dBc for a 40 channel system. 20 channel CTB levels of less than 55 dBc have been verified. Work is under way to improve the measurement system so lower levels of distortion can be measured.

CONCLUSION

The tree-and-branch network shows promise as a cost effective method of bringing fiber closer to the home. The optical amplifier provides the required gain to offset branching and transmission loss. The bandwidth provided by standard CATV fiber is essentially unlimited. The optical amplifier provides a low-noise, extremely large gain-bandwidth product to support wideband transmission of information. The literature does not indicate any fundamental reason that fiber optical amplifiers cannot support amplitude modulation. frequency modulation with microwave sub-carrier modulation has already been demonstrated successfully with semi-conductor and Erbium fiber amplifiers. Recent work indicates that an output power of 20 mW can be delivered by a fiber optical amplifier.

Fiber optics technology is developing at a rapid rate. As these optical technologies develop, costs will reduce and CATV will evolve to utilize the new technology. The evolutionary approach using AM-VSB signals has the best chance of driving fiber further into the system. With the advances in linear AM lasers, power splitting is becoming practical, thereby lowering the cost of a link. On the near horizon is the promise of optical amplifiers capable of supporting AM-VSB signals. The positive aspect of this is that true optical tree-and-branch architectures are possible terminating at bridger stations, then line extenders and perhaps, with more implementation, at the tap. With the present cost of terminal equipment, it will be a long time until it is economical to take fiber to the home. The present goal should be to get fiber further into the system. VSB-AM is the most difficult but most cost-effective modulation format. As cost effective digital systems become available in future years, the installed network will evolve to support them.

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