AN FM/FDM/IM/WDM FIBER OPTIC SUPERTRUNK FOR REPEATERLESS TRANSMISSION OF 10 VIDEO CHANNELS UP TO 45 KM

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ABSTRACT

A repeaterless transmission system capable of transmitting ten video and two, 1.544 MBit/s, digital channels over one singlemode fiber up to distances of 45 km was developed. The system consists of ten wideband Frequency Modulation modems, two digital modems, two long wavelength laser diodes that are both in the 1300 nm range and approximately 50 nm apart, and a specially developed Wavelength Division Multiplexer pair with a total insertion loss of 2.5 dB. The received video signal quality meets or exceeds the Rs-250-B long haul standard and the uncorrected Bit Error Rate is less than 1.0x10E-9. The number of channels and wavelengths can be changed to meet specific link length and optical margin requirements. A description of the system as well as test results are presented.

INTRODUCTION

The application of fiber optic technology in cable television is rapidly advancing, especially since reliable fiber optic components are becoming commercially available. Fiber optics provides many technical advantages when compared to coaxial systems. Amoung the advantages are low attenuation, broad bandwidth, and no electromagnetic interference. Other advantages of using fiber optics are theft security, no need for FCC clearance, small physical size, and upgrade capabilities.

Philips Laboratories, a division of North American Philips Corporation, developed a high capacity, long distance, repeaterless fiber optic supertrunk with Magnavox CATV. Cost analyses have shown that the developed system becomes cost competitive with conventional coaxial systems for link lengths of approximately 10 km and longer.

MAGNAVOX CATV FIBER OPTIC SUPERTRUNK

10 CH/FIBER REPEATERLESS SINGLE MODE FIBER SYSTEM FM/FDM, WDM 1.3µm

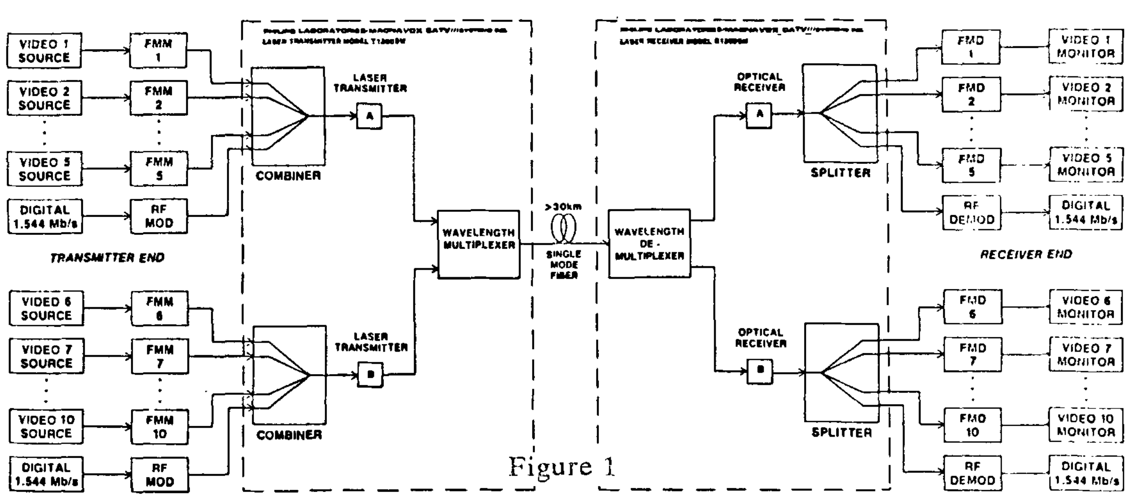


Figure 1

SYSTEM DESCRIPTION

The system configuration is shown in Figure 1. The system consists of 10 wideband Frequency Modulation (FM) modems, whose output signals are Frequency Division Multiplexed (FDM) in pairs of 5. These multiplexed signals Intensity Modulate (IM) two long wavelength laser diodes. The two light signals are Wavelength Division Multiplexed (WDM) into one singlemode fiber. For this purpose a special low loss, low crosstalk, and reliable WDM device was developed. By multiplexing two wavelengths that are both in the 1300 nm range, the low loss and maximum bandwidth window of the singlemode fiber is fully utilized. In addition to the ten video channels, it is possible to transmit two, 1.544 MBit/s, digital signals. The number of channels as well as the number of wavelengths can be changed to meet specific link length and optical margin requirements.

Nonlinearities and low dynamic range of wideband fiber optic links make it impossible to achieve high carrier-to-noise ratios. However, the detected video signal-to-noise ratios (SNR) have to be relatively high. It is therefore necessary to use a modulation method that requires low carrier-to-noise ratios. Two practical schemes are: i) converting the analog video into a digital video signal, or ii) FM modulation of the video signals. The least expensive and least complex of these systems today is the FM modulation of the video signals.

The FM modulators accept baseband video and audio signals at their inputs. The diplexed FM equipment first FM modulates the audio onto a 5.8 MHz carrier, using pre-emphasis, after which it is combined with the baseband video signal to form the composite signal. This composite signal is again FM modulated in the second stage of the FM modems after passing through a second pre-emphasis network. The frequency deviation of the wideband FM modems is equal to 8 MHz (sync-tip to reference white) and the FM enhancement factor is approximately 28 dB when compared with a Vestigial Sideband Modulated (VSB) video signal. The demodulated and de-emphasized video and audio signals are available at the outputs of the FM demodulators. By using wideband FM modulation and by transmitting only 5 channels per laser, the system is relatively insensitive to laser nonlinearities. This is especially important since laser nonlinearities tend to increase during the laser's lifetime.

Each of the digital modems accepts a TTL data stream with bit rates up to 1.544 Mbit/s. The modems use Frequency Shift Keying (FSK) and the output carrier of each modulator is frequency division multiplexed with 5 FM video signals. The measured uncorrected Bit Error Rate, after transmission, is less than 1.0x10E-9.

The optical transmitter is a wideband (450 MHz), analog laser transmitter with good linearity and low group delay distortion capable of carrying several wideband FM video channels. The major functions performed by these circuits are as follows: 1) laser diode temperature stabilization; 2) laser diode optical bias power stabilization; 3) laser diode optical modulation depth stabilization; 4) power combining and controllable attenuation of the individual frequency modulated carriers; 5) Automatic Gain Control (AGC) of the frequency division multiplex of carriers; 6) status monitoring of laser temperature, thermoelectric cooler current, and laser bias current; and finally 7) protection of the laser diode from power current surges.

The laser diodes are thermoelectrically cooled to an accurately controlled temperature. Since the operating wavelength of a laser is temperature dependent,it is possible to fine-tune the lasers. This useful feature makes it possible to relax the wavelength specifications to about a 10 nm range, which reduces the price and increases the availability of the lasers. The operating wavelengths are equal to 1275 nm (@ ~ 7°C) for the short wavelength laser and 1316 nm (@ ~ 20°C) for the long wavelength laser.

The receivers have a bandwidth of about 280 MHz. This allows some freedom in the allocation of the channel frequencies, which makes it possible to minimize the effects of laser nonlinearities (current or future). The optical power required at the input of the receiver, for a weighted video SNR of 54dB, is approximately -30 dBm.

Of the many types of optical fiber available, only multimode graded index and singlemode fiber need to be considered for long distance high bandwidth applications. While multimode has a limited bandwidth-distance product it allows a more efficient coupling of laser power than singlemode which has a much greater bandwidth-distance product. Furthermore, singlemode fiber systems do not suffer from modal noise; a noise source that can cause some serious limitations in multimode systems.

The demonstration fiber link consists of a 0.5 inch diameter fiber optic cable, which contains 24 singlemode fibers interconnected to form a continuous link of 31.2 km. With the above system configuration, this cable has a capacity of 240 channels.

WAVELENGTH MULTIPLEXING

Wavelength division multiplexing can be used to increase the capacity of the system. In wavelength division multiplexing the output of several laser diodes with different wavelengths are multiplexed into one fiber. The cost of the multiplexer is usually far outweighed by the savings in fiber.

Fiber attenuation and fiber dispersion are important considerations in wavelength division multiplexing. The dispersion has its minimum at approximately 1300 nm. At this wavelength the fiber has its maximum bandwidth. The fiber attenuation is also very low at this wavelength. Although the attenuation is even lower at 1500nm , the dispersion at this wavelength is quite large which results in a greatly reduced bandwidth. Other long wavelengths that are sometimes used are, 1100 nm, and 1200 nm. At these wavelengths, both the attenuation and dispersion are larger than at 1300 nm. Use of a wavelength other than 1300 nm will therefore result in a reduced number of channels or in a shorter link. Unfortunately there is only a very narrow window of low attenuation around 1300 nm. For typical fiber this window begins at approximately 1260 nm and ends at 1330 nm. This leaves about 70 nm in which one can assign its wavelengths. Due to this very narrow band, the optical filters have to be very sharp in order to guarantee low crosstalk.

Figure 2 shows a wavelength demultiplexer. It consists of two gradient index (GRIN) rod lenses and an interference filter. The input fiber, carrying two distinct wavelengths, is positioned slightly off axis on the face of a 1/4 pitch lens. The beam is projected and falls incident on a dichroic interference filter. The filter is designed to transmit one wavelength and reflect the other. The reflected beam is then focused and launched into an optical fiber. The transmitted beam is also focused onto another optical fiber. In singlemode applications, the demultiplexer's input fiber is singlemode and the output fibers are multimode. However for a multiplexer, singlemode fiber is used throughout. All the fibers in the multiplexer and demultiplexer must be singlemode for a two-way singlemode system.

Figure 3 shows the transmission curves of the interference filter selected for the device. Maximum transmission occurs at 1270 nm and 1315 nm. One can also see that the acceptable windows of transmission are from 1260 nm to 1275 nm and 1310 nm to 1330 nm. The slope of the short wave curve for wavelengths longer than 1275 nm is 8 dB/10 nm and for the long wave curve it is 10 dB/10 nm for wavelengths shorter than 1310 nm.

Figure 4 shows the measured insertion loss versus wavelength for both the multiplexer (dashed lines) and demultiplexer (solid lines). The optimum wavelengths are 1270 $\pm$ 5 nm and 1315 $\pm$ 5 nm. The wavelengths can be tuned over a short range in order to minimize the total loss of both fiber and WDM device. At these wavelengths the fiber attenuation is approximately 0.5 dB/km and the dispersion is approximately 4 ps/(nm-km). At 1275 nm and 1316 nm, the total insertion loss of both the multiplexer and demultiplexer is approximately 2.5 dB. Optical crosstalk in the 1275 nm channel is approximately -29 dB (equivalent to -58 dB electrical) and -27 dB in the 1316 nm channel (equivalent to -54 dB electrical). With wideband FM modulation, this results in crosstalk levels that are more than 30 dB below noise level.

LINK BUDGET CALCULATIONS

The demonstrated total fiber length is 31.2 km and consists of 18 fibers of 1.73 km each. Additional fiber attenuation was simulated with an optical attenuator. Table 1 lists the optical link budget. The lasers have a maximum coupled output power of 1 mW. The bias point of the laser is set at 500 μW or -3.0 dBm. The insertion loss of the multiplexer is approximately -1.5 dB. The two connectors had a total loss of -1.0 dB maximum. The fiber attenuation was equal to 0.45 dB/km. Average splice loss equaled -0.12 dB. There are 19 splices in the link and therefore the total link loss equaled 31.2 x 0.45 + 19 x 0.12 = 14.0 + 2.3 - 16.3 dB or 0.52 dB/km. The insertion loss of the demultiplexer is -1.0 dB. In the actual setup, the number of splices was somewhat higher due to the fact that the multiplexers and laser were pigtailed before the connectors were attached. However, even if (for some reason) this would be necessary, the link loss would not increase significantly. In fact, due to rapid improvements in splicing equipment it is very likely that in future links, the total link loss can be reduced to an even lower value.

The receiver sensitivity is -30.0 dBm for a video signal to noise ratio of 54 dB and one digital and 5 video channels per laser. The actual received optical power (without optical attenuator) is -22.8 dBm. This gives an optical margin of 7.2 dB. This was verified with the optical attenuator.

Inserting an additional 8 fiber lengths of 1.73 km each plus 8 additional splices will give an additional loss of 8 x 0.52 = 7.2 dB. This is equal to the optical margin. Insertion of an equivalent additional length will give a total link length of 31.2 + 8 x 1.73 = 45.0 km, with no optical margin. In a real installation one always wants some margin to compensate for future degradations. However, a 7.2 dB margin is probably too conservative. Inserting 4 instead of 8 fiber lengths would have given an additional loss of 4 x 1.73 x 0.52 = 3.6 dB. So the total link length in this case would be 31.2 + 4 x1.73 = 38.1 km with an optical margin of 7.2 - 3.6 = 3.6 dB. The latter case is probably more suitable for an actual installation since it would allow some 30 additional splices or some significant drop in laser output power over the system's lifetime.

TABLE 1

coupled laser power (bias)		-3.0 dBm
multiplexer loss		-1.5 dB
total connector loss (2)		-1.0 dB
fiber attenuation	-0.45 dB/km	
link length	31.2 km	
total fiber loss		-14.0 dB
splice loss	-0.12 dB	
number of splices	19	
total splice loss		-2.3 dB
demultiplexer loss		-1.0 dB
received power		-22.8 dBm
receiver sensitivity	-30.0 dBm	
optical margin	7.2 dB	

(number of channels = 12 : 10 video + 2 digital)

SYSTEM PERFORMANCE

The received video signal quality meets or exceeds the RS-250_B [1] long haul standard. The received video signal to noise ratio is equal to 54 dB [2]. The use of singlemode fiber makes it possible to use a bandwidth of 280 MHz that was only limited by the receiver. This gives some freedom in frequency assignments which, together with the use of wideband FM modems, makes the system relatively insensitive to nonlinearity distortions. Any future increase in laser nonlinearity distortion (due to aging or other effects) will therefore not affect the system to the degree it would in a system that uses narrowband FM modems. Furthermore, the system is also less sensitive to instabilities in the FM equipment, since the separation between the various channels is quite large. Optical crosstalk is far below the required value and does not degrade the signals.

The uncorrected bit error rate is equal to 1.0x10E-9. The digital channels are not affected by the video signals and nonlinearity distortions. Insertion of the digital signals does not reduce the video signal quality, nor does it reduce the optical margin.

Preliminary investigations show that two-way transmission will be possible with the current WDM device if the multimode pigtails out of the demultiplexer are replaced with singlemode pigtails.

It is possible to reconfigure the system. For longer link lengths the WDM device can be left out. This will increase the received optical power by approximately 2.5 dB and transmissions up to 50 km should be possible. The number of channels would then be reduced to 6 (5 video and one digital). It is also possible to increase the number of channels if the link length is reduced or if the WDM device is taken out. Finally, link length and/or the number of channels can be traded off against the amount of optical margin.

CONCLUSIONS

A fiber optic supertrunk for repeaterless transmission of ten high quality video and two 1.544 Mbit/s digital channels, up to a distance of 45 km over a single fiber was developed. Tests with the system have shown that even substantial increases in nonlinearities will not degrade the signals significantly. The developed WDM device makes it possible to increase the number of channels per fiber and allows both wavelengths to be in the optimum 1300 nm region.

The number of channels, the long transmission distance, and the many advantages of fiber optic technology, will make these types of systems an attractive alternative for many conventional systems.

REFERENCES

(1) Electrical Industries Association, Standard RS-250-B, "Electrical Performance Standards for Television Relay Facilities", Sept. 1976, Washington, DC.

(2) Straus, T.M., "The Relationship Between the NCTA, EIA, and CCIR Definitions of Signal-To-Noise Ratio", IEEE Trans. on Broadcastings, BC-20,#3, Sept. 1974, pp. 36-40.

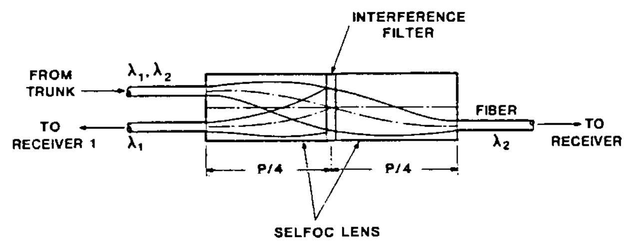


Figure 2

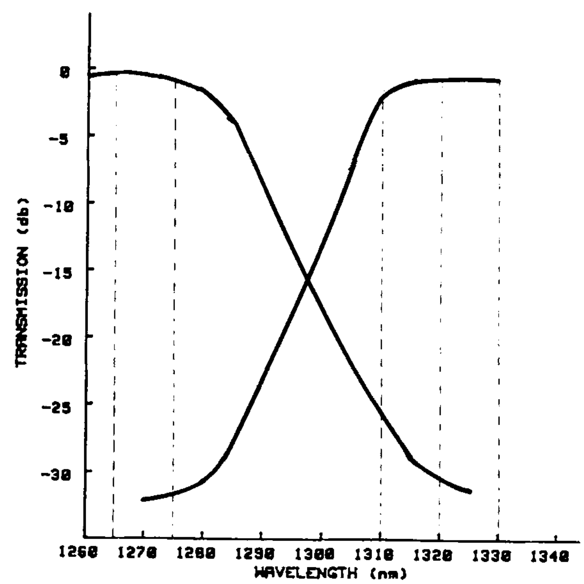
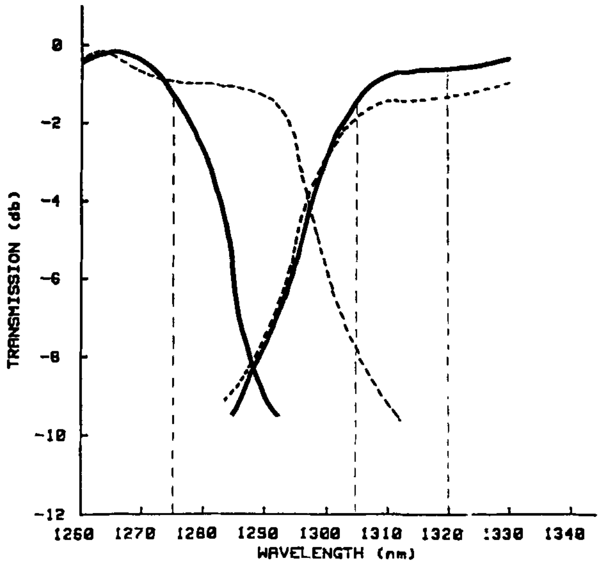


Figure 3


TRANSMISSION (db)
0
-2
-4
-6
-8
-10
-12
1260 1270 1280 1290 1300 1310 1320 1330 1340
WAVELENGTH (nm)
Figure 4