Improvements in Fiber-Optic Transmission of Multi-Carrier TV Signals

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***Abstract*—In broadband networks, there is an increasing need for the transmission of more and more television channels with a higher quality. For this purpose the optical transmission proved to be one of the best solutions. However, when the number of TV channels is high, a significant harmonic and intermodulation distortion will arise. These distortions can be reduced by improving the modulation linearity of the laser or by applying a more appropriate modulation method. In this paper both solutions will be discussed and evaluated in detail. The linearity has been significantly improved by applying an active matching technique. The improvement achieved via the new driving circuit over the conventional one is 15 dB considering the third harmonic distortion. The sensitivity of QPSK TV transmission to disturbing interferences has been investigated. A new so called "group modulation" method offers a better approach for optical multi-carrier TV transmission.**

I. Introduction

In BROADBAND networks, there is an increasing need for the transmission of more and more TV (television) channels with a higher quality. For this purpose the optical transmission proved to be one of the best solutions. The fiber-optic link offers a very wideband transmission with adequate signal-to-noise ratio [1]. However, when the number of TV channels is high a significant harmonic and intermodulation distortion will arise because of the nonlinearities in the fiber-optic link [2], [3]. However, the modulation nonlinearity of the semiconductor laser is the dominant factor [4]–[7].

The distortions can be reduced by improving the modulation linearity of the laser or by applying a more appropriate modulation method. In this paper both solutions are discussed and evaluated in detail. The different system arrangements are compared.

The linearity has been significantly improved by applying an active matching technique. The sensitivity of QPSK (quadrature phase shift keying) TV transmission to disturbing interference has been experimentally investigated. A new "group modulation" method offers a better approach for optical multi-carrier TV transmission.

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II. Improvements in the Transmitter Linearity

At the transmitter side, a linear transfer is needed from the microwave input to the optical output. In the generally used cases, at the input of the transmitter dozens of TV channels are multiplexed utilizing individual subcarriers. Thus the band lies in the lower UHF frequency range, the spectrum is confined to a band of several hundred MHz. When the number of TV channels or their bandwidth is to be increased, the overall band is extended into the higher UHF or microwave frequency range. However, the spectrum has no components below a few hundred MHz.

The nonlinearity of the transmitter provides the most significant contribution to the nonlinearity of the complete fiber-optic link. Therefore, any improvement in the transmitter linearity has a great significance [8]. The linearity of the transmitter is influenced by the modulation characteristic of the laser and the transfer function of the driving circuit. The laser linearity is dependent mainly on its inner construction. Thus the transmitter linearity can be improved significantly by the proper choice of the laser construction. However, this paper will be concentrated on the improvements achieved by a more appropriate driving circuit.

A. Laser Input Impedance

For improving the linearity of the transmitter, the microwave input impedance of the semiconductor laser has to be determined first. This measurement was carried out on a double heterostructure diode laser in the frequency range of 100 to 1500 MHz at several bias currents. The laser was operated around 800 nm wavelength. A typical result measured at 300 MHz is plotted in Fig. 1 showing the real and imaginary parts of the input impedance of the laser diode as a function of the bias current. As seen in this figure, the real part of the input impedance is significantly decreased with increasing laser current, however, the imaginary part of the input impedance depends on the bias current only when it is not high enough.

The nonlinear input resistance contributes significantly to the nonlinearity of the modulation characteristics of the laser if the usual passive matching techniques are applied [9], [10]. Therefore, an active matching technique has been developed to obtain a better linearity.

The microwave input impedance of the semiconductor laser also shows a significant frequency dependence as

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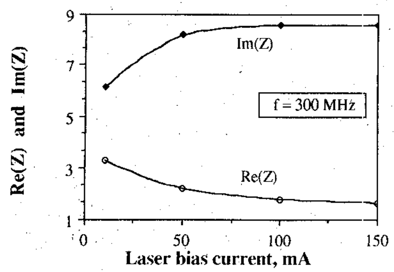

Fig. 1. The real and imaginary parts of the microwave input impedance versus the laser bias current.

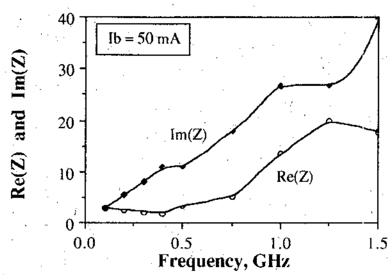

Fig. 2. The real and imaginary parts of the microwave input impedance versus modulation frequency.

seen in Fig. 2 where the real and imaginary parts of the laser input impedance are plotted as functions of the frequency for a laser bias current of 50 mA. Both the real and imaginary parts of the laser input impedance are increasing with the frequency. However, around 1250 MHz a discrepancy is observed both in the real and imaginary parts of the laser input impedance because the real part shows a local maximum and the imaginary part exhibits a local minimum there. That refers to a resonance at this frequency.

The goal is to obtain a wide transmission band with a high linearity. To design the matching circuit in accordance with this goal, an accurate equivalent circuit for the microwave input impedance of the laser has been derived. Based on the measured data, a six element equivalent circuit has been derived applying a curve fitting method utilizing the Nelder–Mead algorithm and MatLab software. The derived equivalent circuit is presented in Fig. 3. The parasitic elements are constant: $L_2 = 2.9$ nH and $C_2 = 1.6$ pF. The other elements of the equivalent circuit are level dependent. These are plotted in Figs. 4 and 5.

Fig. 4 presents R_1 and C_1 while Fig. 5 L_1 and R_2 as functions of the laser bias current. R_1 shows a significant decrease with increasing laser bias current. However, C_1 depends on the bias current only when it is not high enough. That statement is valid for L_1 and R_2 as well. A nonlinear inductance is usually representing an avalanche effect.

The result of curve fitting is seen in Fig. 6 where the reflection coefficients are plotted in a polar diagram. The crosses show the measured values, and the solid curve gives the reflection coefficient of the six element equivalent circuit. The parameter of the curve is the frequency. The agreement between the measured data and that of the

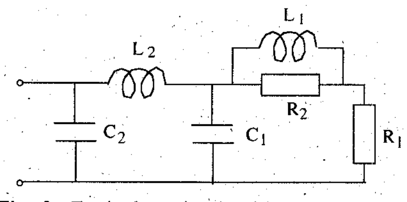

Fig. 3. Equivalent circuit with six elements.

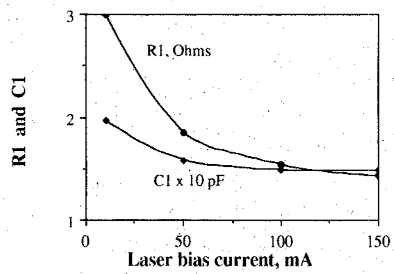

Fig. 4. The R_1 and C_1 elements of the equivalent circuit as functions of the laser bias current.

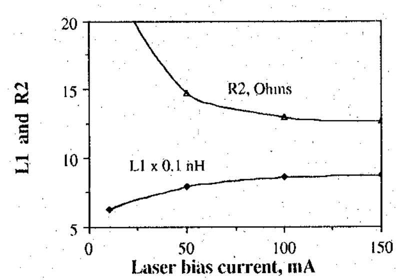

Fig. 5. The R_2 and L_1 elements of the equivalent circuit as functions of the laser bias current.

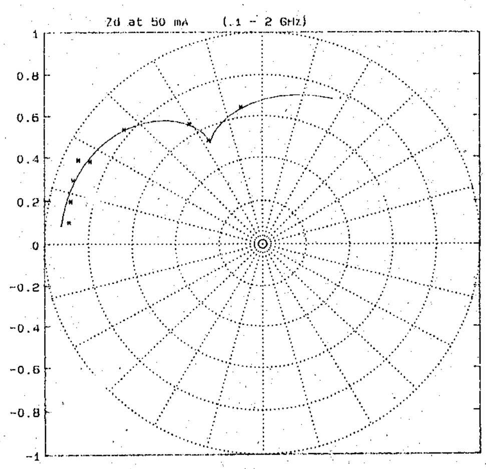

Fig. 6. The reflection curve of the equivalent circuit with the measured values.

equivalent circuit is excellent. Around 1.25 GHz the previously mentioned resonance effect is observed because there is a sudden change in the reflection curve.

Referring to Fig. 6 it is seen that a much better matching can be achieved when the transmission is carried out in two separated bands: one below 1.25 GHz and another one above 1.25 GHz. In this case the effect of the resonance in the input impedance around 1.25 GHz can be avoided.

B. Driving Circuit

The active matching has been performed by a new driving circuit. The main task of that driving circuit is to provide a good transfer from its voltage driven input to its current driven output for the laser diode. This goal has been achieved by the active matching technique what is needed because the load of the driving circuit, i.e., the microwave input impedance of the laser is nonlinear. As this impedance is frequency dependent as well the proper frequency response of the driving circuit is also necessary for a higher linearity. Utilizing these matching processes, a significant improvement has been attained in the modulation linearity of the laser.

The new driving circuit is shown in Fig. 7. It contains a MESFET and two bipolar transistors, providing the appropriate feedback and input-output matching. A photodiode (PD) is used for the indication of the output optical power. An operational amplifier serves for protecting the laser diode (LD) utilizing the signal of the monitoring photodiode. The microwave part of the driving circuit was built in a microstrip construction with direct connection to the laser diode.

The inner conductance of the driving circuit has to be chosen properly as well because the load is nonlinear. The nonlinear load generates harmonics, thus the level of the harmonics characterizes the nonlinearity.

First, only a second power nonlinearity is assumed for the load:

$$I(t) = a_1 V(t) + a_2 V(t)^2 \quad (1)$$

where $I(t)$ is the time function of the current flowing through the nonlinear load, $V(t)$ is the time function of the voltage across the terminals of the nonlinear load, and a_1 and a_2 are coefficients.

The nonlinear load is driven by a current source with a source current I_0 and with an inner conductance G_g. For the second harmonic generated in the laser G_g represents the load as well. The transfer function is given as the ratio of the fundamental frequency voltage V_1 across the terminals of the nonlinear load and the source current I_0 which is given as follows:

$$\frac{V_1}{I_0} = \frac{1}{a_1 + G_g} \frac{1}{1 - \frac{1}{2} \frac{a_2^2}{(a_1 + G_g)} V_1^2}. \quad (2)$$

The transfer function is nonlinear because it is dependent on V_1. With increasing V_1 the nonlinearity of the transfer function is enhanced. If G_g is increasing the nonlinearity will be smaller. A higher G_g means a lower parallel resistance which provides a better linearity, however, a lower transfer at the same time.

A similar relationship is obtained for the third harmonic distortion as well. However, the case of the intermodulation distortion is more complicated because it is dependent on the spectrum of the modulating signal, too.

Both the input impedance of the laser and the output impedance of the driving circuit are nonlinear. These two parallel connected nonlinear elements can be combined and described by a single nonlinear element representing the resultant nonlinearity. By this way some compensation can also be achieved with the aim to linearize the complete transfer function.

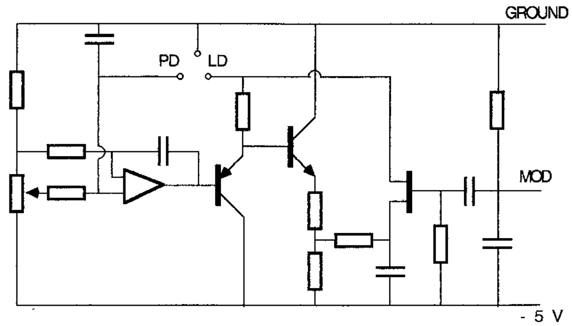

Fig. 7. Circuit diagram of the driving circuit.

The bias current of the laser has to be chosen properly as well. The most linear section of the modulation characteristic is to be used and special care is needed to keep the bias current unchanged under a high level modulation as well.

The distortion of the transmission is also dependent on the width and center of the band to be transmitted. The adequate separation from the relaxation oscillation is a further relevant requirement because the transfer function of the laser is significantly affected by the relaxation oscillation, and that is contributing to the nonlinear distortion as well.

III. Measurement of Nonlinearity

Many well established methods are available to measure the nonlinearity or its result. The nonlinearity gives rise to harmonic and intermodulation distortions and interferences between the channels.

The characterization of the nonlinearity is influenced by the specific type of application. First, the harmonic distortion measurement method has been applied to determine the linearity as a function of the modulating signal level. The harmonic content of the output spectrum has been measured for that purpose. The result is shown in Fig. 8 where the output levels of the fundamental, second and third harmonic frequency signals are plotted as functions of the 70 MHz fundamental frequency input level. The harmonic levels are small enough. E. g. with an input signal at −5 dBm level, the third harmonic distortion is at −50 dBc. That is a very low level indeed. This result can be used in general as a measure of the improvement achieved via the new driving circuit over the conventional one which provided only a −35 dBc level for the third harmonic distortion with the same input signal level. Thus the improvement is 15 dB. At the −5 dBm input signal level the optical modulation depth (OMD) was approximately 12%.

The linearity has been checked by investigating the mixing effect as well. A 350 MHz signal with 0 dBm constant input level served as a local oscillator signal, and

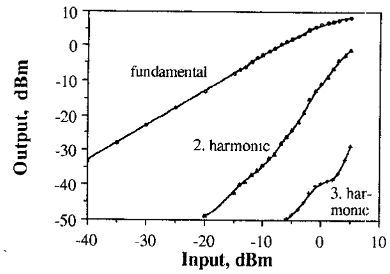

Fig. 8. The output level of the fundamental, second and third harmonic frequency signals as functions of the fundamental frequency input level.

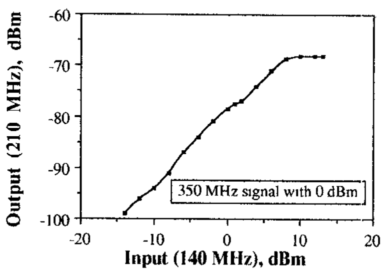

Fig. 9. The input-output curve in case of mixing two signals.

the input level of the other signal with a frequency of 140 MHz was varied. The output was obtained at 210 MHz. The result of this investigation is presented in Fig. 9. As seen the mixing product is extremely small indicating a very low nonlinearity.

IV. More Appropriate Modulation Methods

The linearity requirement can be less stringent when a more appropriate modulation method is used.

In the widely used arrangements, the TV channels are transmitted in their original form containing AM (amplitude modulated) video and FM (frequency modulated) sound channels. For combining several tens of TV channels subcarriers are applied and the combined signal is then used to modulate the optical transmitter.

A significant improvement can be obtained if analog or digital frequency or phase modulation is applied for the individual video channels. The frequency or phase modulation is less sensitive to the nonlinearities as it was already demonstrated [11]–[14].

In many cases the source of the television signals is an earth station of a direct broadcasting satellite system, and there frequency modulated TV signals are received. Thus the FM-AM conversion is preferably made not at the earth station but at the other end of the optical link, and this way FM TV signals are transmitted via the optical fiber link.

A further approach offers a good transfer for digitalized TV signals. A QPSK (quadrature phase shift keying) modulation method can be used for the individual TV channels because this modulation method is also not sensitive to the nonlinearities. In our experiments the optical transmission of a pseudo-random QPSK signal with a frequency of 70 MHz and with a bit rate of 34 Mbit/s was

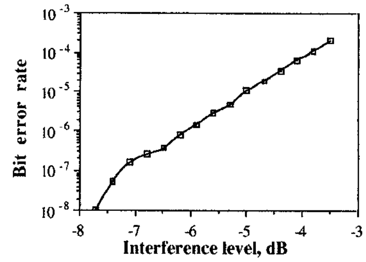

Fig. 10. Bit error rate as a function of the distorting signal level.

investigated concerning the interference effects. The impairment in the bit error rate was measured as a function of the distorting signal level at 70 MHz obtained from the other unmodulated carriers via the nonlinear conversion. That is shown in Fig. 10 where the bit error rate (BER) is plotted as a function of the distorting interference level. As seen in this Figure the interfering signal is at a very high level when the impairment in the bit error rate is noticeable.

Finally, by an appropriate allocation of the subcarrier frequencies, the intermodulation distortion and the interference can be reduced significantly.

V. Group Modulation

Now another new approach is presented which will be called "group modulation." In this case, 5 to 10 TV channels with different subcarriers create a group, and this group is put on a second subcarrier modulating its frequency. That is shown in Fig. 11 providing the block diagram of a complete optical link applying the new group modulation technique. In a group the analog or digital TV channels are combined by having different subcarriers. The output signals of the group modulators with the second subcarriers are led via a branching filter to the laser diode which is modulated in intensity. At the receiver side after the optical detection group discriminators are used to regain the TV signals with the first subcarriers. To achieve not too wide relative bandwidth in the group modulation, the second subcarrier frequency has to be high compared with the bandwidth of a group.

The group modulation is more advantageous because the linearity requirement in a group is less stringent and it can easily be met by the group modulator and demodulator. The frequency modulated groups are much less sensitive to the nonlinearity of the optical transmission considering the interference problems. Further, the signal-to-noise ratio can be enhanced by increasing the frequency deviation. Creating the groups also offers new possibilities: the proper choice of the frequency bands for the groups assures a lower interference level.

The group modulation is a good approach to ease the linearity requirements when the number of TV channels is very high [15]. The reason is that the modulation nonlinearity of the group modulator and demodulator can be kept at a very low level. This technique has another advantage: the groups can be separated by branching filters

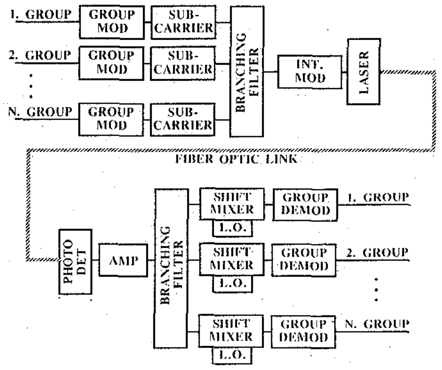

Fig. 11. Block diagram of the optical link applying group modulation.

which makes possible a more flexible operation, e.g., when a group is to be dropped out or a new group has to be inserted. The advantages of the group modulation are more remarkable if HDTV channels are to be transmitted.

Certainly, the best solution is achieved by the application of all distortion reduction approaches presented in this paper. However, the linearity improvement obtained by the active matching technique presumably will be applied in most cases because of its relative simplicity, while the group modulation technique can get an application mainly in the trunk lines, e.g., for the transmission of HDTV channels.

VI. Conclusion

The demand for higher transmission capacities is based on the need for more available TV channels, and also on the wish for improving the quality of the TV transmission. In the future, more and more HDTV programs will be distributed which require a wider bandwidth. Another trend is the application of digital modulation for the transmission of TV channels which also needs a wider band.

The increase in the capacity of the fiber-optic links achieved by improved linearity and by applying a new modulation method can be exploited for the transmission of more analog or digital TV or HDTV channels. That will be a relevant application in the near future.

References

[1] C. H. Cox III, D. Z. Tsang, L. M. Johnson, and G. E. Betts, "Low-loss analog fiber-optic links," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, 1990, pp. 157–160.

[2] T. E. Darcie and G. E. Bodeep, "Lightwave subcarrier CATV transmission systems," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 524–533, May 1990.

[3] J. Lipson, L. C. Upadhyayula, S. Y. Huang, C. B. Roxlo, E. J. Flynn, P. M. Nitzsche, C. J. McGrath, G. L. Fenderson, and M. S. Schaefer, "High-fidelity lightwave transmission of multiple AM-VSB NTSC signals," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 483–493, May 1990.

[4] W. I. Way, "Large signal nonlinear distortion prediction for a single-mode laser diode under microwave intensity modulation," *J. Lightwave Technol.*, vol. LT-5, pp. 305–315, 1987.

[5] P. A. Morton, R. F. Ormondroyd, J. E. Bowers, and M. S. Demokan, "Large-signal harmonic and intermodulation distortion in wide-bandwidth GaInAsP semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 25, pp. 1559–1567, 1989.

[6] M. L. Majewski and L. A. Coldren, "Distortion characteristics in directly modulated laser diodes by microwave signals," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Long Beach, CA, June 1989.

[7] K. Y. Lau and A. Yariv, "Intermodulation distortion in a directly modulated semiconductor injection laser," *Appl. Phys. Lett.*, vol. 45, no. 10, pp. 1034–1036, 1984.

[8] S. Iezekiel, C. M. Snowden, and M. J. Howes, "Nonlinear circuit analysis of harmonic and intermodulation distortions in laser diodes under microwave direct modulation," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1906–1915, Dec. 1990.

[9] T. Berceli, "Optical-to-microwave interactions," URSI General Assembly, Prague, Czechoslovakia, Sept. 1990.

[10] T. Berceli, "Linearity problems of lasers," *Seminar on Optical-Microwave Interactions*, Technical University of Budapest, Sept. 1990.

[11] D. J. Heatley and T. G. Hodgkinson, "Video transmission over cabled monomode fiber at 1523 nm using PFM with 2-PSK heterodyne detection," *Electron. Lett.*, vol. 20, pp. 110–112, 1984.

[12] D. J. Heatley, "Unrepeated video transmission using PFM over 100 km of monomode optical fiber," *Electron. Lett.*, vol. 18, pp. 369–371, 1982.

[13] C. N. Lo and L. S. Smoot, "Integrated fiber optic transmission of FM HDTV and 622 Mb/s data," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Long Beach, CA, June 1989, pp. 703–704.

[14] D. D. Tang, "Multi-Gigabit fiber-optic video distribution network using BPSK microwave subcarriers," *IEEE MTT-S Int. Microwave Symp. Dig.*, Long Beach, CA, June 1989, pp. 697–701.

[15] T. Berceli, I. Frigyes, P. Gottwald, P. R. Herczfeld, and F. Mernyei, "Performance improvements in fiber-optic links for multi-carrier TV transmission," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Boston, MA, June 1991.

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