

Large-Signal Theory of the Effect of Dispersive Propagation on the Intensity Modulation Response of Semiconductor Lasers

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Abstract—We have derived an exact large-signal theory of propagation in a dispersive fiber of an optical wave with sinusoidal amplitude and frequency modulation. This has been applied to the study of large-signal direct-modulation of semiconductor lasers. It is shown that the large-signal response can significantly deviate from the predictions of the small-signal theory. In particular, the improvement in modulation response caused by frequency-to-intensity modulation conversion in propagation that occurs with small-signal modulation is no longer achieved with large-signal modulation, which could affect systems such as dispersion supported transmission. Experimental results confirm our theory.

Index Terms—Frequency modulation, intensity modulation, optical fiber communication, optical fiber dispersion, optical fiber measurement applications, semiconductor lasers.

I. INTRODUCTION

THE technologically important problem of the effect of dispersive fiber propagation on the intensity modulation response of semiconductor lasers has been treated in the past by assuming either small-signal modulation [1], [2] or low dispersion [3]. In this work we extend the analysis to the case of large-signal and arbitrary dispersion, which more closely approximates conditions in intensity modulation-direct detection (IM-DD) systems. We show that the highpass behavior of the fiber transfer function that is predicted by the small-signal theory [1] is degraded as the amplitude of the modulation signal is increased. This could affect systems that use dispersion to enhance the modulation response after propagation in fiber, such as dispersion supported transmission [1], or after a fiber Bragg grating [4].

II. THEORY

A. 1-Tone Large-Signal Modulation

Semiconductor lasers exhibit chirp, i.e., the frequency of the optical field is modulated whenever the intensity is modulated. To a first approximation, the intensity and frequency of the light generated by a laser directly modulated at a frequency $\Omega/2\pi$

vary linearly with modulation (the general case is considered below). The complex electric field amplitude, \tilde{E} , at the laser output can be expressed in the form

$$\begin{aligned} \tilde{E}(t, z = 0) \\ = P_0^{1/2} (1 + m_{\text{IM}} \cos(\Omega t + \varphi_{\text{IM}}))^{1/2} e^{im_{\text{FM}} \sin(\Omega t + \varphi_{\text{FM}})} \end{aligned} \quad (1)$$

where P_0 is the average output power, m_{IM} and m_{FM} are the intensity modulation (IM) and frequency modulation (FM) indexes, respectively, and φ_{IM} and φ_{FM} are the corresponding phases. The ratio $(m_{\text{FM}}/im_{\text{IM}})e^{i\Delta\varphi}$, where $\Delta\varphi = \varphi_{\text{FM}} - \varphi_{\text{IM}}$, will be referred to in what follows as the phase-to-intensity (modulation index) ratio, PIR. For light produced by a semiconductor laser, the PIR is a function of the modulation frequency, and can be expressed as

$$\text{PIR} \equiv \frac{m_{\text{FM}}}{im_{\text{IM}}} e^{i\Delta\varphi} = -\frac{\alpha}{2} \left(1 + \frac{\kappa(\Omega)}{i\Omega} \right) \quad (2)$$

where α is the linewidth enhancement factor, and $\kappa(\Omega)$ is related to several laser parameters and contributes to a quasi-adiabatic chirp [5], [6].

Equation (1) indicates that the electric field spectrum consists of sidebands at harmonics of the modulation frequency centered on the laser optical frequency. Due to group velocity dispersion, linear propagation in a dispersive optical fiber produces a phase change of the sidebands relative to the optical carrier, which results in partial conversion of FM into IM, which is then photodetected at the fiber output.

Small-signal analyses have been previously proposed that only take into account the fundamental sideband at the modulation frequency. This is a reasonable approximation for transmitters with no chirp, but it does not well describe semiconductor laser light, which exhibits large frequency modulation even for relatively small intensity modulation. In the analysis presented here we assume that the IM can be still linearized, but keep the exact form of the FM. Thus, the IM is approximated by an amplitude modulation (AM) as follows:

$$\begin{aligned} (1 + m_{\text{IM}} \cos(\Omega t + \varphi_{\text{IM}}))^{1/2} \\ \cong m_0 (1 + m_{\text{AM}} \cos(\Omega t + \varphi_{\text{IM}})) \end{aligned} \quad (3)$$

where, as a first approximation, $m_0 \cong 1$ and the AM index $m_{\text{AM}} \cong m_{\text{IM}}/2$ (see Appendix A for a more accurate expression for m_0 and m_{AM}). By using (3) and expanding the FM as

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a series of Bessel functions [7], the electric field amplitude can be written as:

$$\begin{aligned} \tilde{E}(t, z=0) &\cong P_0^{1/2} \left(1 + \frac{m_{\text{IM}}}{2} \cos(\Omega t + \varphi_{\text{IM}}) \right) e^{im_{\text{FM}} \sin(\Omega t + \varphi_{\text{FM}})} \\ &= P_0^{1/2} \sum_{n=-\infty}^{\infty} c_n(z=0) e^{in(\Omega t + \varphi_{\text{IM}})} \end{aligned} \quad (4)$$

$$\begin{aligned} c_n(z=0) &= e^{in\Delta\varphi} \left[J_n(m_{\text{FM}}) + \frac{m_{\text{IM}}}{4} \right. \\ &\quad \left. \cdot (J_{n+1}(m_{\text{FM}})e^{i\Delta\varphi} + J_{n-1}(m_{\text{FM}})e^{-i\Delta\varphi}) \right]. \end{aligned} \quad (5)$$

In propagation through the fiber the different harmonics acquire different phase changes due to dispersion. The harmonic amplitude at z can be expressed as

$$c_n(z) = e^{in^2\theta(z)} c_n(0) \quad (6)$$

where $\theta(z) = -(1/2)\beta_2\Omega^2z$, β_2 is the fiber dispersion parameter and z is the fiber length. The detected photocurrent, $\tilde{I}_{\text{det}}(t, z)$, is obtained by squaring the electric field amplitude. In previous analyses, this was calculated either numerically [8] or by using the small-signal approximation. Here, we have applied a summation theorem of the Bessel functions [7] to derive the exact \tilde{I}_{det} for an electric field with AM and FM as in (4), and is given by

$$\tilde{I}_{\text{det}}(t, z) = \sum_{n=-\infty}^{\infty} I_{\text{det}}(n\Omega, z) e^{in(\Omega t + \varphi_{\text{IM}})} / L(z) \quad (7)$$

$$\begin{aligned} I_{\text{det}}(n\Omega, z) &= R(n\Omega) P_0 i^n e^{in\Delta\varphi} \\ &\quad \cdot \left[J_n(u) - i \frac{m_{\text{IM}}}{2} \cos n\theta \right. \\ &\quad \left. (J_{n-1}(u)e^{-i\Delta\varphi} - J_{n+1}(u)e^{i\Delta\varphi}) \right] \end{aligned} \quad (8)$$

where $u = 2m_{\text{FM}} \sin n\theta$, $I_{\text{det}}(n\Omega, z)$ photocurrent at the n th harmonic; $R(n\Omega)$ photodiode responsivity at frequency $n\Omega$; $L(z)$ fiber power loss in linear units.

The fiber modulation transfer function relates the photodetected current at the modulation frequency after and before propagation in dispersive fiber. From (8), we obtain

$$H_{fib}(\Omega, z) = \cos \theta (J_0(u) - J_2(u)e^{i2\Delta\varphi}) - 2 \frac{e^{i\Delta\varphi}}{im_{\text{IM}}} J_1(u) \quad (9)$$

which simplifies in the small-signal approximation to the well-known expression

$$\begin{aligned} H_{fib}(\Omega, z) &\approx \cos \theta - 2 \frac{m_{\text{FM}}}{im_{\text{IM}}} e^{i\Delta\varphi} \sin \theta \\ &= \cos \theta - 2\text{PIR} \sin \theta. \end{aligned} \quad (10)$$

Equation (10) indicates that the small-signal fiber transfer function only depends on known fiber properties, namely β_2 and fiber length, and the PIR, which is a laser intrinsic property. In fact, by measuring the small-signal fiber transfer function for several lengths of fiber, the laser PIR can be determined as a

function of modulation frequency [5]. In addition, from (8) (or (16) in Appendix A) and (9) we observe that the large-signal response of the laser after propagation in fiber is also fully characterized by the laser PIR and the laser intensity modulation index m_{IM} .

B. N-Tone Large-Signal Modulation

The analysis presented in the previous section can be extended to the case of an input signal consisting of an arbitrary number N of tones at angular frequencies Ω_k (and also the case where the nonlinear dynamics of the laser cannot be neglected). The complex electric field envelope can be expressed as

$$\begin{aligned} \tilde{E}(t, z=0) &\cong P_0^{1/2} \left(1 + \sum_{k=1}^N \frac{m_{\text{IM}k}}{2} \cos(\Omega_k t + \varphi_{\text{IM}k}) \right) \\ &\quad \cdot \exp \left(i \sum_{k=1}^N m_{\text{FM}k} \sin(\Omega_k t + \varphi_{\text{FM}k}) \right). \end{aligned} \quad (11)$$

By using the same type of analysis as above, we obtain that the detected signal after propagation in dispersive fiber is given by

$$\begin{aligned} \tilde{I}_{\text{det}}(t, z) &= \sum_{n_1, n_2, \dots, n_N=-\infty}^{\infty} I_{\text{det}} \left(\sum_{k=1}^N n_k \Omega_k, z \right) \\ &\quad \cdot \exp \left(i \sum_{k=1}^N n_k (\Omega_k t + \varphi_{\text{IM}k}) \right) / L(z). \end{aligned} \quad (12)$$

The photodetected intensity for the intermodulation product (IMP) $\Omega_{\text{IMP}} \equiv \sum_{k=1}^N n_k \Omega_k$ is given by

$$\begin{aligned} I_{\text{det}}(\Omega_{\text{IMP}}, z) &= R(\Omega_{\text{IMP}}) P_0 i^{\sum_{k=1}^N n_k} \exp \left(i \sum_{k=1}^N n_k \Delta\varphi_k \right) \\ &\quad \cdot \prod_{k=1}^N (J_{n_k}(u_k)) \left[1 - \sum_{k=1}^N i \frac{m_{\text{IM}k}}{2} \cos \theta_k \right. \\ &\quad \left. \cdot (J_{n_k-1}(u_k)e^{-i\Delta\varphi_k} - J_{n_k+1}(u_k)e^{i\Delta\varphi_k}) / J_{n_k}(u_k) \right] \end{aligned} \quad (13)$$

where $u_k = 2m_{\text{FM}k} \sin \theta_k$ and $\theta_k = -(1/2)\beta_2\Omega_k\Omega_{\text{IMP}}z$. The total intermodulation distortion at a particular frequency is equal to the sum of all the IMP's in (12) that fall onto that frequency.

In Appendix B the theory here developed is applied to the case of a typical CATV transmission system.

III. SIMULATION

In this section, the validity of the approximation in (3), i.e., linearization of the laser IM, is verified by comparison with the exact analysis. The laser PIR is assumed to be that of the MQW-DFB laser tested below ($\alpha t \cong -4$). Fig. 1 shows the modulation transfer function after 85 km of standard fiber for several intensity modulation indexes. It is observed that the large-signal fiber transfer function deviates significantly

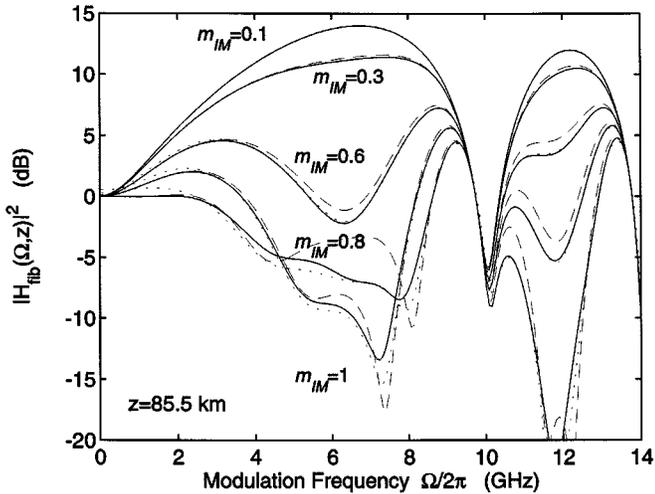


Fig. 1. Numerical simulations of fiber modulation transfer function after propagation in 85 km of fiber for different modulation indexes. Dashed from (9), dotted from (16) and solid is exact.

from the small-signal model for intensity modulation indexes greater than 0.2. On the contrary, (16) remains accurate even for intensity modulation indexes close to unity. The major discrepancy occurs at the dips of the transfer function, where the received intensity is very small and the effect of the small IM sidebands becomes more important.

Comparison of (9) and (10) (as can also be observed in Fig. 1) indicates that the maximum of the fiber transfer function for any given laser parameters occurs at the *smallest* intensity modulation. Thus, the enhancement of modulation response due to propagation that is attained in the small-signal regime is suppressed as m_{IM} is increased. This could pose severe limitations to systems such as dispersion supported transmission [1] that rely on the improvement in the modulation response to combat dispersion.

IV. EXPERIMENT

The predictions of our large-signal theory have been compared to the measured photocurrent of light from a directly-modulated MQW-DFB laser at 1.55 μm after propagation in several lengths of standard fiber. The resonance frequency, the damping coefficient and the PIR were determined from the small-signal modulation response before and after propagation in fiber. The method presented in [5] allows precise determination of the PIR. Here, we used instead a simpler method that consists of fitting the small-signal transfer function to the theoretical PIR for a MQW laser [6]. This method is accurate enough and overcomes the problems encountered with other oversimplified techniques (see [5] for more details). The intensity modulation index, m_{IM} , was determined by measuring the modulation response before propagation in fiber and subtracting the response of the receiver (photodiode + amplifier). The receiver spectral response was determined by using the amplified spontaneous emission noise of an erbium-doped fiber amplifier as white noise source. The absolute value of the receiver gain was measured by using the known spectral density of shot noise.

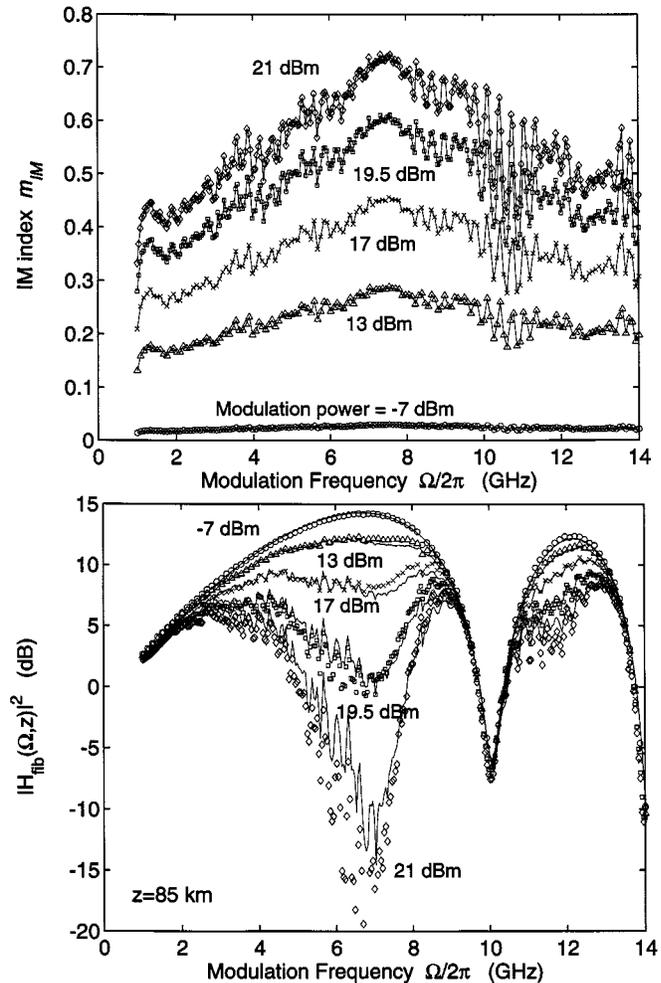


Fig. 2. (a) Intensity modulation index measured at the laser output for several modulation powers. (b) Fiber modulation transfer function after propagation in 85 km of fiber for the same modulation powers as in (a). Solid curve is theory.

Fig. 2(a) shows the measured intensity modulation index, m_{IM} , as a function of modulation frequency at the laser output for several modulation powers. The frequency dependence of m_{IM} is due to both the laser driving electronics and the laser dynamics. This m_{IM} together with the PIR, measured in the small-signal regime as described above, were used to predict the large-signal fiber transfer function, $H_{fib}(\Omega, z)$, for 85 km of fiber. This is plotted in Fig. 2(b) (solid) together with the experimental data points. As m_{IM} increases, the highpass behavior that is attained with small-signal modulation (circles) is degraded. At very large m_{IM} , our theory does not perfectly agree with the experiment due to the presence of IM harmonics (and consequently FM harmonics) at the laser output that were neglected in (1), and not to the approximation in (3). This was verified by estimating the effect of these higher order terms in the modulation response (a complete determination of the modulation response including these terms was not possible because the relative phase between the IM harmonics was not known).

We have also measured the harmonic distortion after propagation in fiber. Fig. 3(a) shows the power in the modulation frequency, Ω , and in higher order harmonics of Ω (normalized by the power in the optical carrier) in dBc at the laser output

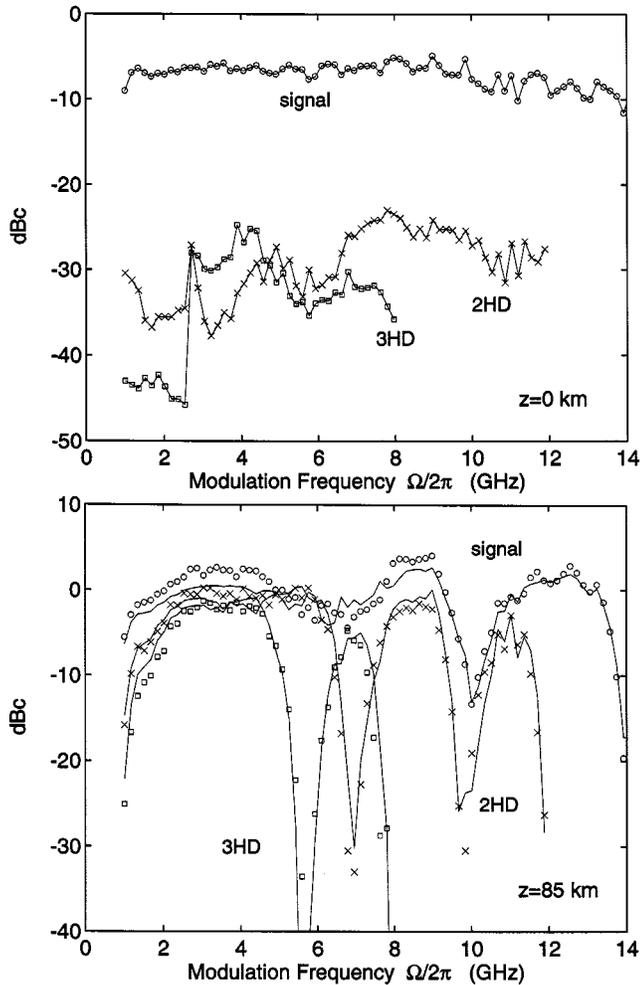


Fig. 3. Experimentally detected power in signal (circles), second harmonic (crosses) and third harmonic (squares) normalized by the power in the carrier in dBc, (a) at the laser output, (b) after propagation in 85 km of fiber. Solid curve is theory.

($z = 0$). The harmonic distortion at the laser output comes from the poor spectral purity of our signal generator, and also to a smaller degree from the nonlinearity of the laser dynamics. The measured power in the modulation tone at Ω (higher order IM harmonics were not included in the analysis) together with the PIR were used to predict harmonic distortion after propagation in 85 km of fiber. This theory is shown in Fig. 3(b) (solid curve), and agrees well with the experiment. Thus, we can conclude that in our case the main source of harmonic distortion after propagation comes from beating of the FM sidebands and is well described by (16). It is also observed in Fig. 3(b) that the power in the harmonics exhibits the same characteristics as that in the modulation tone, namely peaks and dips that repeat more rapidly as Ω increases and as the order of the harmonic increases.

The intermodulation distortion was measured by modulating the laser with two tones at angular frequencies Ω_1 and $\Omega_2 = 0.9 \Omega_1$. Fig. 4 shows the detected signal before and after propagation in fiber (in dBc) at the modulation tone frequencies and in the IMP $\Omega_2 - \Omega_1$, which agrees with our theoretical prediction (solid curve).

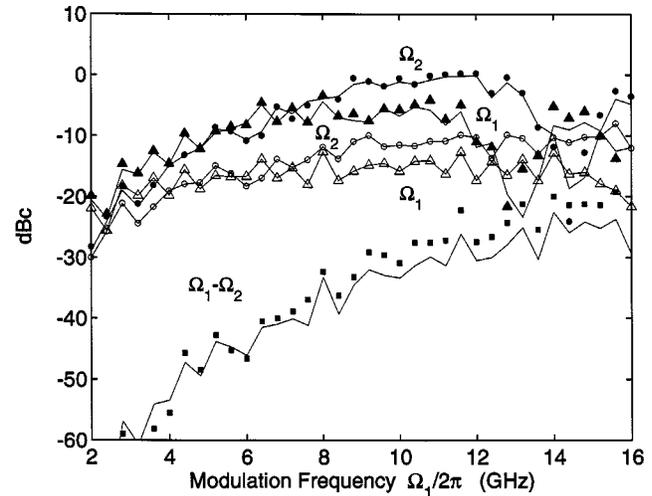


Fig. 4. Experimentally detected normalized power in dBc for 2-tone modulation at the laser output at Ω_1 (open triangles) and $\Omega_2 = 0.9 \Omega_1$ (open circles) and after propagation in 50 km of fiber at Ω_1 (solid triangles), Ω_2 (solid triangles) and $\Omega_1 - \Omega_2$ (solid squares). Solid curve is theory.

V. CONCLUSION

The exact large-signal theory of dispersive propagation of an optical wave with sinusoidal amplitude and frequency modulation was derived and applied to the study of large-signal direct-modulation of semiconductor lasers. Thus, an expression for the intermodulation distortion after fiber propagation for modulation with an arbitrary number of input tones was obtained. This expression fully characterizes transmission of light produced by semiconductor lasers in dispersive (linear) fiber in the frequency domain. In fact, the nonlinear transfer functions (or Volterra kernels) that describe the transmission can be derived from it straightforwardly. This analysis could be applied to the design of pre- and/or postdistortion circuits or carrier phase management schemes in SCM systems, for example to reduce intermodulation distortion. The same type of analysis as presented here has also been used to characterize dispersive propagation of light from externally frequency and/or amplitude modulated lasers, and will be subject of a future publication.

APPENDIX A

A MORE ACCURATE AND AN EXACT LARGE-SIGNAL THEORY

In (4) the AM index was approximated by $m_{\text{IM}}/2$. We can instead expand the IM, i.e., the left-hand side of (3), as a Fourier series

$$(1 + m_{\text{IM}} \cos(\Omega t + \varphi_{\text{IM}}))^{1/2} \cong \sum_l m_l e^{i l \Omega t} \quad (14)$$

where the Fourier coefficients, m_l , are given by [7]

$$m_l = (-1)^{l+1} \sum_{n=0}^{\infty} \frac{(4n + 2l - 3)!!}{(4n + 2l)!!} \binom{2n + l}{n} \left(\frac{m_{\text{IM}}}{2}\right)^{2n+l}. \quad (15)$$

By keeping only the AM sideband at the modulation frequency, i.e., by using the approximation (3) with $m_{\text{AM}} = 2m_1$, we

obtain that the detected photocurrent at frequency $n\omega$ is given by

$$I_{\text{det}}(n\Omega, z) = R(n\Omega)P_0 i^n e^{in\Delta\varphi} \cdot [m_0^2 J_n(u) + 2im_0 m_1 \cos n\theta \cdot (J_{n+1}(u)e^{i\Delta\varphi} - J_{n-1}(u)e^{-i\Delta\varphi}) + 4m_1^2 (2J_n(u) \cos 2n\theta - J_{n-2}(u)e^{-i2\Delta\varphi} - J_{n+2}(u)e^{i2\Delta\varphi})], \quad n \geq 1. \quad (16)$$

In Section III, we show that the above expression is very accurate even for intensity modulation indexes close to unity.

If all the harmonic sidebands of the IM in (14) are taken into account, we obtain

$$I_{\text{det}}(n\Omega, z) = R(n\Omega)P_0 \sum_{l, l'=-\infty}^{\infty} i^{n+l-l'} m_l m_{l'} \cdot e^{i(n+l-l')\Delta\varphi} e^{in\theta(l+l')} J_{n+l-l'}(u). \quad (17)$$

Equation (17) is exact for an electric field with IM and FM. The double infinite sum in (17) converges fast and only a few terms are needed. This is simpler than previous formulations [8] that involved four infinite sums with slower convergence.

APPENDIX B

INTERMODULATION DISTORTION IN CATV SYSTEMS

As an example of the theory developed in this paper, we consider transmission of N NTSC channels of CATV. At the typical CATV frequencies, the laser chirp is mostly adiabatic, and can be approximated by

$$\text{PIR} \cong -\frac{\alpha \kappa_0}{2 i\Omega}. \quad (18)$$

For moderate propagation distances

$$u_k \cong 2m_{FM_k} \theta_k \cong \frac{1}{2} m_{IM_k} \alpha \kappa_0 \beta_2 z \Omega_{\text{IMP}} = u_k(\Omega_{\text{IMP}}, z). \quad (19)$$

Thus, the value of the IMP's depends only on the frequency of the intermodulation product, ω_{IMP} , but not on the frequency of the beating tones.

In CATV systems, small intensity modulation indexes are usually employed in order to avoid clipping of the signal. By substituting (19) into (13), and using a power series expansion of the Bessel functions, we obtain

$$I_{\text{det}}(\Omega_{\text{IMP}}, z) \cong R(\Omega_{\text{IMP}})P_0 \prod_{k=1}^N \left(\frac{m_{IM_k}^{|n_k|}}{|n_k|!} \right) \cdot (i\Omega_{\text{IMP}}\xi)^n \left(1 + \frac{n}{2i\Omega_{\text{IMP}}\xi} \right) \quad (20)$$

where $\xi = (1/4)\alpha\kappa_0\beta_2 z$ and $n = \sum_{k=1}^N |n_k|$ is the order of the IMP.

Assuming that all channels have the same intensity modulation index, $m_{IM_k} = m_{\text{IM}}$, the n th-order intermodulation distortion (IMD $_n$) normalized by the power in the RF carrier is approximately given by

$$\text{IMD}_n(\Omega, z) \approx \frac{A_n(\Omega)}{(n-1)!} (m_{\text{IM}} i\Omega\xi)^{n-1} \quad (21)$$

where

$$A_n(\Omega) = \sum_{\substack{i_1, \dots, i_n=1 \\ \Omega = \pm\Omega_{i_1} \pm \dots \pm\Omega_{i_n}}}^N e^{i(\pm\varphi_{\text{IM}_{i_1}} \pm \dots \pm\varphi_{\text{IM}_{i_n}})}. \quad (22)$$

From (21) and (22), it becomes evident that by proper management of the carrier phases it should be possible to affect the intermodulation distortion spectrum.

For uncorrelated carriers the total intermodulation distortion IMD is

$$\text{IMD}(\Omega, z) \approx \sum_n N_n(\Omega) \left| \frac{(m_{\text{IM}}\Omega\xi)^{n-1}}{(n-1)!} \right|^2 \quad (23)$$

where $N_n(\Omega) = \langle |A_n|^2 \rangle$ is the number of beats for that order.

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