For the TM mode, the small factor is $\exp[-\alpha_{ec}(b - a)]$. As for the TE mode, for the TM mode also, the metal cladding introduces a small reflected wave in the buffer layer $a < x < b$ and a small transmitted wave in the metal. The transmitted field in the metal is of the form

$$H_{yp} = B_{1e} e^{ik_{pe}(x-b)} e^{i\beta_e z} \tag{31}$$

where

$$k_{pe} = \left(\omega^2 \epsilon_p - \beta_e^2\right)^{1/2} \tag{32}$$

and B_{1e} is the transmitted field amplitude at $x = b$. The small field reflected at the metal surface modifies the field in the buffer layer as

$$H_{yc} = N_e A_e e^{-\alpha_{ec}(x-a)} e^{i\beta_e z} + C_{1e} e^{\alpha_{ec}(x-b)} e^{i\beta_e z} \tag{33}$$

where C_{1e} is the reflected field amplitude at the metal surface. The required boundary conditions at the metal surface are

$$H_{yp} = H_{yc} \qquad \text{at } x = b \tag{34}$$

$$\frac{1}{\epsilon_p}\frac{\partial}{\partial x} H_{yp} = \frac{1}{\epsilon_c}\frac{\partial}{\partial x} H_{yc} \quad \text{at } x = b \tag{35}$$

When Equations (31) and (33) are substituted in Equations (34) and (35) and C_{1e} is eliminated from the resulting equations, we find that

$$B_{1e} = \frac{i2\alpha_{ec}/\epsilon_c}{k_{pe}/\epsilon_p + i\alpha_{ec}/\epsilon_c} N_e A_e e^{-\alpha_{ec}(b-a)} \tag{36}$$

The z component of the electric field corresponding to Equation (31) is determined as

$$E_{zp} = -\frac{k_{pe}}{\omega \epsilon_p} H_{yp} \tag{37}$$

As in Equation (17), the net guided wave power entering the volume through the planes at z and $z + dz$ is given by

$$P(z) - P(z + dz) = -\frac{dP}{dz} dz = 2\alpha_{g,\mathrm{TM}} |A_e|^2 \, dz \tag{38}$$

where $\alpha_{g,\mathrm{TM}}$ is the field attenuation coefficient of the TM guided mode. From Equations (31) and (37), the power dissipated in the metal inside the volume shown in Figure 1 is derived as

$$P_{\mathrm{diss}} = \frac{1}{2} \mathrm{Re}\left[-H_{yp} E_{zp}^*\right]_{x=b} dz\, w = \frac{\mathrm{Re}\left[k_{pe}\epsilon_p^*\right]}{2\omega|\epsilon_p|^2} |B_{1e}|^2 \, dz\, w \tag{39}$$

Power conservation requires the results in Equations (38) and (39) to be equal. Then, using Equations (27a), (27b), (29), (30), (36), and the relation

$$\mathrm{Im}\left[-\frac{\epsilon_c k_{pe} - i\epsilon_p \alpha_{ec}}{\epsilon_c k_{pe} + i\epsilon_p \alpha_{ec}}\right] = \frac{2\epsilon_c \alpha_{ec} \mathrm{Re}\left[k_{pe}\epsilon_p^*\right]}{\left(\epsilon_c k_{pe} + i\epsilon_p \alpha_{ec}\right)\left(\epsilon_c k_{pe}^* - i\epsilon_p^* \alpha_{ec}\right)} \tag{40}$$

we determine the field attenuation coefficient of the guided TM mode as

$$\alpha_{g,\mathrm{TM}} = \frac{4\epsilon_f \alpha_{ec} \epsilon_c k_e \exp[-2\alpha_{ec}(b-a)]}{z_B\left(\epsilon_f^2 \alpha_{ec}^2 + \epsilon_c^2 k_e^2\right)} \times \mathrm{Im}\left[-\frac{\epsilon_c k_{pe} - i\epsilon_p \alpha_{ec}}{\epsilon_c k_{pe} + i\epsilon_p \alpha_{ec}}\right] \tag{41}$$

where

$$z_B = \frac{2\beta_e}{k_e}\left[2a + \epsilon_f \frac{\epsilon_c}{\alpha_{ec}} \frac{k_e^2 + \alpha_{ec}^2}{\epsilon_c^2 k_e^2 + \epsilon_f^2 \alpha_{ec}^2} + \epsilon_f \frac{\epsilon_s}{\alpha_{es}} \frac{k_e^2 + \alpha_{es}^2}{\epsilon_c^2 k_e^2 + \epsilon_f^2 \alpha_{es}^2}\right] \tag{42}$$

IV. CONCLUDING REMARKS

The attenuation coefficient of the guided mode supported by the metal-clad planar dielectric waveguide for both the transverse electric and the transverse magnetic modes has been obtained rigorously using a quasioptical technique [5, 6]. The quasioptical result is asymptotically exact to the first order in the small parameter $\exp[-2\alpha_{vc}(b - a)]$ with $v = h$ for the TE mode and $v = e$ for the TM mode. The results deduced here in Equations (20) and (41) by a perturbation technique that is commonly used for metallic waveguides are identical to the asymptotically exact quasioptical results. For the usual parameters of the metal-clad planar dielectric waveguide, there is excellent agreement between the results deduced numerically from the exact dispersion relation and those evaluated from the perturbation results given in Equations (20) and (41) [6].

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SIGNAL AND NOISE IN A COHERENT OPTICAL COMMUNICATION SYSTEM USING RAMAN AMPLIFIER

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KEY TERMS

Coherent optical communications, Raman amplifier

ABSTRACT

We present analytical expressions for the signal and the amplified spontaneous emission (ASE) noise in a coherent optical system using Raman amplification. The results show that the signal spectrum is unaffected by the amplifier and the ASE noise can be thought of as additive white Gaussian noise within the signal bandwidth.

INTRODUCTION

In coherent optical fiber communications systems, the means to provide signal amplification are important issues [1]. The currently used amplifier or repeater in optical communications systems needs complicated optical–electrical–optical conversion and demodulation–modulation circuits. Furthermore, the electrical amplifier bandwidth is limited to tens of GHz. In contrast, fiber Raman amplifiers, providing direct optical amplification by using stimulated Raman scattering, are broadband and high gain [2–4]. In addition, a fiber Raman amplifier which can simultaneously amplify multiple-channel signals is attractive in a frequency-division-multiplexed coherent system. Here we investigate the signal and noise of a Raman amplifier in a coherent system.

ANALYSIS

Let A and α denote the effective Raman cross section and the loss coefficient of a single-mode fiber with a transmission length L. To simplify the analysis, we consider a Lorentzian Raman gain profile with bandwidth W_g [5]. It is assumed that the pump is a continuous wave. Let $S(0, \nu_s)$ and $P(0, \nu_p)$ denote the signal and the pump spectral components injected at $z = 0$ and traveling in the $+z$ direction. The Raman process is governed by a second order nonlinear differential equation. The interaction between the signal and the pump in an intensity modulation–direct detection fiber system was investigated in [4] where the signal and the pump were assumed to be single frequency lasers, in this case the effect of their spectral distributions is neglected and the Raman gain is assumed to be constant. However, in a coherent system using a semiconductor laser as a light source, the spectrum of the signal is an important factor which strongly influences system performances. Therefore, to fully investigate the use of Raman amplifiers in a coherent system, the spectral distributions of the signal and the pump should be taken into consideration and the Raman gain should not be assumed to be constant. In our derivation, the signal and the pump spectra are considered to be Lorentzian distributed with full-width–half-maximum linewidths W_s and W_p, respectively. For simplicity, we consider the nondepleted pump condition. Then the differential equations are written as

$$\frac{dS(z,\nu_s)}{dz} = -\alpha S(z,\nu_s) + \frac{\phi(\nu_s)}{A}\left[S(z,\nu_s) + h\nu_s\right] \quad (1)$$

$$P(z,\nu_p) = P(0,\nu_p)e^{-\alpha z} \quad (2)$$

where

$$\phi(\nu_s) = \int g(\nu_p - \nu_s)P(z,\nu_p)\,d\nu_p \quad (3)$$

We can analytically solve (1) by using the integrating factor technique [6]. Then the signal and the forward ASE noise are obtained as

$$S(z,\nu_s) = S(0,\nu_s)e^{-\alpha z}\exp[\psi(\nu_s)(1 - e^{-\alpha z})] \quad (4)$$

$$N(z,\nu_s) = h\nu_s\psi(\nu_s)\exp[-\alpha z - \psi(\nu_s)e^{-\alpha z}] \times[\alpha z + F(\psi(\nu_s)) - F(\psi(\nu_s)e^{-\alpha z})] \quad (5)$$

where

$$\psi(\nu_s) = K\frac{(W_g + W_p)^2}{4(\nu_s - \nu_{s0})^2 + (W_g + W_p)^2} \quad (6)$$

$$K = \frac{g_0 P(0)}{\alpha A}\frac{W_g}{W_g + W_p} \quad (7)$$

$$F(x) = \sum_{n=1}^{\infty}\frac{x^n}{nn!} \quad (8)$$

and ν_{s0} is the center frequency of the signal, g_0 is the peak Raman gain coefficient, $P(0)$ is the initial pump power.

DISCUSSION

The propagation of the signal and the ASE noise are shown in Figures 1 and 2 where $\Delta\nu = \nu_s - \nu_{s0}$. The signal and the ASE noise are first amplified by the pump. After reaching their maximum point they decay when propagating further. Note that the ASE noise spectrum width is much wider than that of the signal. We see that the second term on the right-hand side of (4) is the propagation loss of the fiber and the third term accounts for the Raman amplification for the signal frequency component at ν_s. Since the signal used in a coherent fiber system only has spectral width up to several GHz which is much smaller than the bandwidth of Raman gain profile ($W_g \simeq 7200$ GHz typically), the frequency dependent function $\psi(\nu_s)$ in (6) is nearly constant within the signal linewidth. Thus all the signal frequency components are almost amplified with the same gain so that the signal spectrum is essentially unaffected by the amplification process. This is a desirable feature of Raman amplifiers since little phase noise is introduced in the pumping process. In the following discussions, we assume that $\psi(\nu_s)$ is equal to the universal constant K within the signal band. The amplifier gain can be calculated from (4). We define the amplifier gain at $z = L$ as

$$G = 10\log\frac{S(L)}{S(0)e^{-\alpha L}} \quad (9)$$

where $S(0)$ and $S(L)$ are the transmitted and received signal power at $z = 0$ and $z = L$, given by

$$S(0) = \int S(0,\nu_s)\,d\nu_s \quad (10)$$

$$S(L) = \int S(L,\nu_s)\,d\nu_s = S(0)e^{-\alpha L}\exp[K(1 - e^{-\alpha L})] \quad (11)$$

Assuming $e^{-\alpha L} \ll 1$, we have $G = 4.34K$ which shows that the amplification gain is linearly proportional to the constant K.

Since the ASE noise spectrum is much wider than the signal, we assume that there is an optical filter with bandwidth BW at the input of a coherent receiver so that only in-band

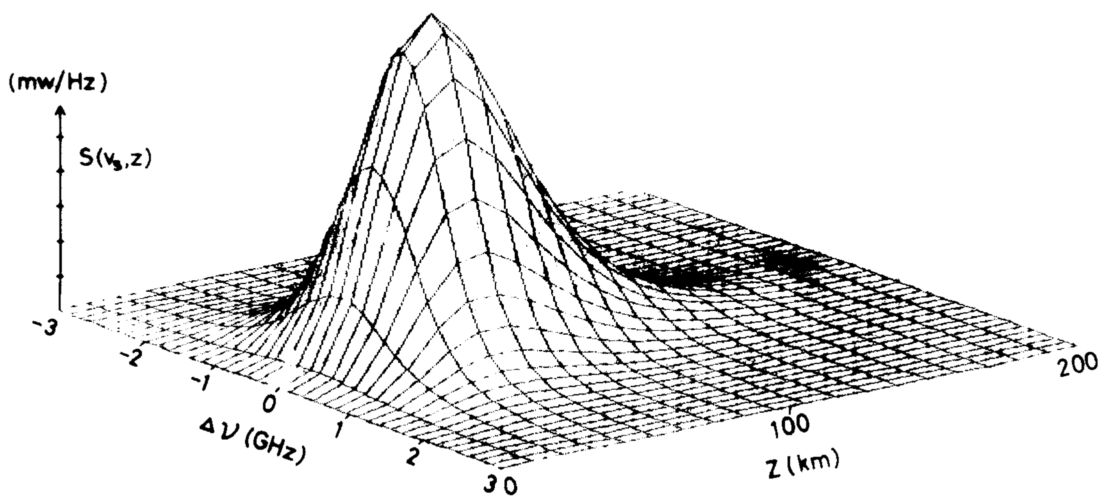

Figure 1 The propagation of signal versus fiber length. $W_g = 240\ \text{cm}^{-1}$, $W_p = 40\ \text{cm}^{-1}$, and $W_s = 1$ GHz

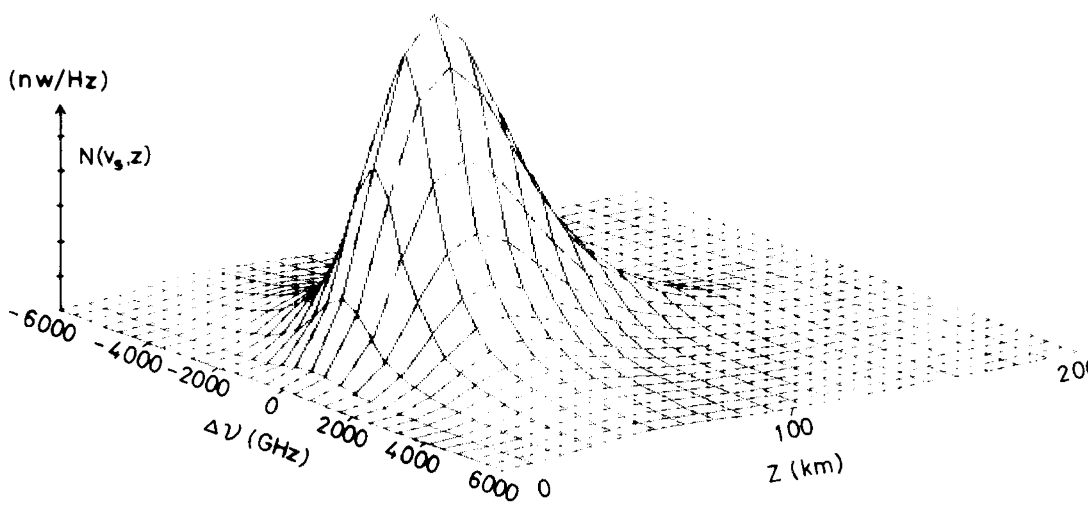

Figure 2 The accumulation of ASE noise versus fiber length

noise will be considered. In general, BW is much smaller than the noise spectral width so that the in-band noise spectrum is approximately equal to $N(L, \nu_{s0})$. In other words, the ASE noise can be treated as additive white Gaussian noise within the signal band. Assume $Ke^{-\alpha L} \ll 1$, the in-band noise power around $z = L$ can be obtained as

$$N(L) = N(L, \nu_{s0})BW$$

$$= h\nu_{s0}Ke^{-\alpha L}[\alpha L + F(K)]BW \qquad (12)$$

From (11) and (12), the signal to noise ratio (SNR) is obtained as

$$\text{SNR} = 10\log\frac{S(L)}{N(L)}$$

$$= 10\log\frac{S(0)e^{K}}{h\nu_{s0}K[\alpha L + F(K)]BW} \qquad (13)$$

The SNR, as a function of the universal constant K, is depicted in Figure 3. We see that SNR improves as K increases. But the improvement becomes smaller when K is getting bigger. Hence we can increase the amplification gain and SNR by increasing K, which is proportional to the pump power and Raman gain constant.

CONCLUSION

In summary we have presented analytical expressions of signal and noise in a coherent communication system with Raman amplification. Their spectral behavior is discussed. The result shows that the phase noise introduced by the Raman amplifier is negligible and the in-band ASE noise can be considered as additive white Gaussian noise. The amplifier gain is linearly proportional to the pump power and inversely proportional to both the fiber loss constant and the effective Raman cross section. By increasing the pump power we can achieve high SNR.

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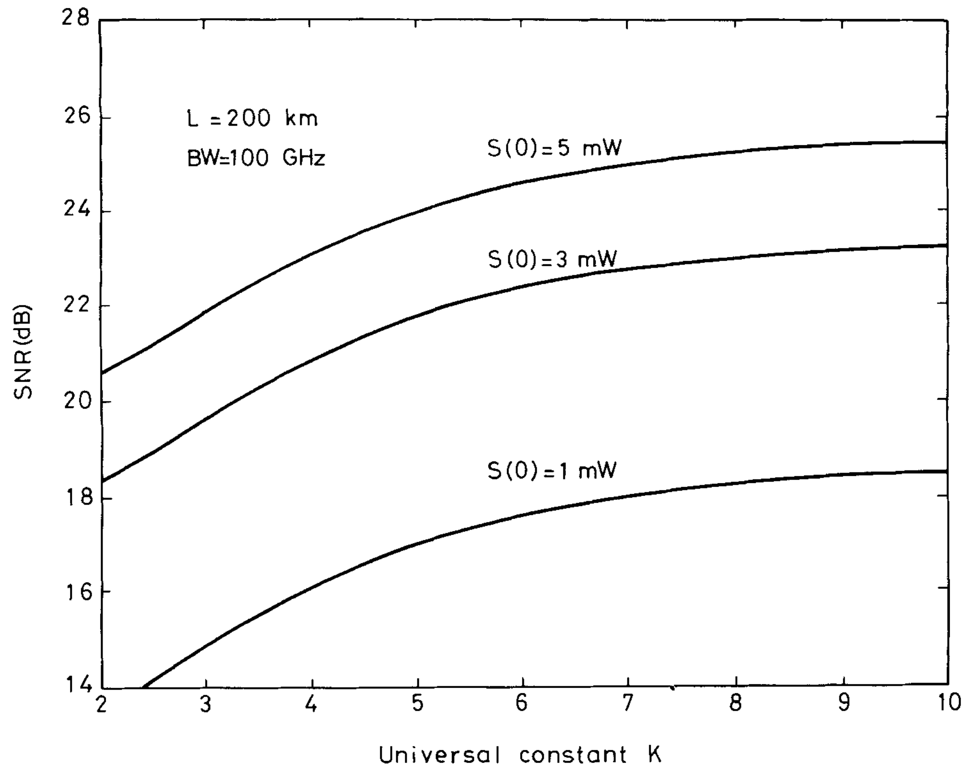

Figure 3 SNR versus the universal constant K

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GENERATION OF MICROWAVE SIGNALS FROM A LASER DIODE COUPLED TO AN EXTERNAL CAVITY

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KEY TERMS

Laser modulation, interferometer, microwave generation from laser diode

ABSTRACT

This article describes a technique by which a laser diode coupled with an external cavity is used in an interferometric system resulting in a direct envelope modulation of the optical carrier. The laser output is fed to a Mach–Zehnder interferometer in which the time delay associated with the path imbalance is adjusted to half the time period T_m of the modulating sawtooth current. The two signals are heterodyned to simulate an envelope modulated optical signal.

INTRODUCTION AND BACKGROUND

Interaction of electrooptics and microwaves is of great importance in the areas of sensing, signal processing, and communications. This includes the generation of radio frequency and microwave signals by optical mixing of two optical signals.

In previous work [1] a modulated laser diode is used to generate r.f. and microwave signals by a self-mixing process, where the laser diode is modulated by a square wave driving current, resulting in a square wave frequency modulation plus a small depth of amplitude modulation. This paper describes an alternative technique by which a laser diode coupled with an external cavity is used in an interferometric system resulting in a direct envelope modulation of the optical carrier.

A sawtooth drive current is applied to a laser diode coupled to an external cavity. In the absence of any feedback from the external cavity, the laser diode output frequency follows the drive current. But with the external cavity of length L, mode hopping takes place with a frequency deviation $\Delta f = c/2L$. By adjusting the external cavity length L and the amplitude of the modulating current, frequency hopping can be limited between two levels.

In the system suggested in this paper, the laser output is fed to a Mach–Zehnder interferometer in which the time delay associated with the path imbalance is adjusted to half the time period T_m of the modulating sawtooth current. The two signals are heterodyned to simulate an envelope modulated optical signal.