Pumping Planar Waveguide Amplifiers Using a Coupled Waveguide System

L. H. Slooff, P. G. Kik, A. Tip, and A. Polman

***Abstract*—A novel scheme is presented that can be used to efficiently pump optical waveguide amplifiers. It is based on the coupling between two adjacent waveguides, where pump light is gradually coupled from a nonabsorbing pump waveguide into the amplifier waveguide. The coupling between the waveguides in such a configuration is calculated using an improved coupled mode theory (CMT). The proposed distributed coupling scheme can enhance the optical gain in systems that exhibit a reduced pumping efficiency at high pump power. A numerical example is given for a sensitized neodymium-doped polymer waveguide amplifier, in which the optical gain increases from 0.005 dB to 1.6 dB by changing from conventional butt-coupling to distributed coupling.**

***Index Terms*—Neodymium compounds, optical amplifiers, optical waveguides theory, rare-earth compounds, waveguide couplers.**

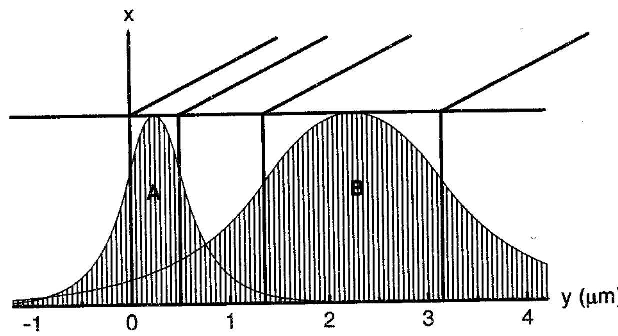

Fig. 1. Schematic presentation of a two-dimensional (2-D)coupled waveguide system consisting of parallel optical waveguides A and B. The calculated waveguide mode intensity along the x axis is shown for the waveguide geometry described in the text (515 nm for pump A, 1.34 μm for pump B).

I. Introduction

THE RAPID expansion of optical telecommunication technology increases the need for planar optical amplifiers that can be used to compensate losses in splitters, switches multiplexers, and other devices. Planar optical amplifiers are widely studied and they often use the rare earth ions erbium or neodymium as the active element because these ions exhibit intra-$4f$ transitions around 1550 nm and 1340 nm, respectively, two of the standard telecommunication wavelengths [1]. Amplification is obtained by optical pumping of the rare-earth ions in order to create population inversion. Stimulated emission induced by the signal light then results in optical amplification.

The pumping of optical waveguide amplifiers is usually done by coupling the pump beam into the waveguide at the input facet of the waveguide (butt-end coupling). The pump light is absorbed by the rare-earth ions as it travels through the waveguide, resulting in a decrease in pump power along the waveguide. In order to maintain sufficient pump power over the entire length of the waveguide, relatively high pump powers are coupled into the input section of the waveguide. This pumping scheme can be successfully used for materials in which high pump powers do not affect the pumping efficiency. However, in several materials systems, an optimum pump power for amplification exists. Such systems include Er-doped waveguides in which cooperative upconversion and excited-state absorption take place [1], or systems in which the rare-earth ions are excited via energy transfer from a sensitizer [2], [3]. In these systems, butt-end coupling is not efficient. The excess pump power at the beginning of the waveguide will result in pump absorption, which does not contribute to the optical gain.

In this paper, we introduce a coupling configuration that can distribute the pump power evenly over the full length of the (signal) waveguide. It is based on the coupling between two waveguides in close proximity. In this scheme, the pump light is gradually coupled from a nonabsorbing pump guide into the adjacent amplifier guide. By gradually increasing the coupling (i.e., reducing the distance between the guides), it is possible to maintain a constant pump power along the signal guide. We will study the coupling between two parallel waveguides using coupled-mode theory (CMT). A numerical example is given that shows that the optical gain of a sensitized Nd-doped polymer waveguide amplifier can be enhanced using this novel pump scheme.

II. CMT for Dissimilar Waveguides

The waveguide structure under consideration is shown in Fig. 1. It consists of pump waveguide A and signal waveguide B. In order to evaluate the performance of this system, we first need to calculate the coupling of pump power into the signal waveguide. This can be done using CMT.

The conventional CMT [4], [5] deals with the coupling between two weakly interacting, nearly identical optical waveguides. The total field of the waveguide system can be written

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as a linear superposition of the individual waveguide modes $\mathbf{E}^a(x,y)$ and $\mathbf{E}^b(x,y)$ as follows:

$$\begin{aligned}\mathbf{E} &= a(z)\mathbf{E}^a(x,y) + b(z)\mathbf{E}^b(x,y)\\ \mathbf{H} &= a(z)\mathbf{H}^a(x,y) + b(z)\mathbf{H}^b(x,y)\end{aligned} \tag{1}$$

with z being the propagation direction. The coupled-mode equations, defining the mode amplitudes $a(z)$ and $b(z)$ along the waveguide, are given by

$$\begin{aligned}\frac{d}{dz}\,a(z) &= i\gamma_a a(z) + ik_{ab}b(z)\\ \frac{d}{dz}\,b(z) &= ik_{ba}a(z) + i\gamma_b b(z)\end{aligned} \tag{2}$$

with $\gamma_{a,b}$ propagation constants and $k_{ab,ba}$ mutual-coupling constants, which, in this case, are identical. If the waveguides are not identical, or in the case of strong coupling, the mutual-coupling coefficients are different for the two waveguides, and, as a result, power is not conserved in the conventional theory. This problem can be dealt with using modified propagation and coupling parameters $\gamma_a, \gamma_b, k_{ab}$, and k_{ba}, as given in Appendix A [6]. These parameters are known nonlinear functions of the fields of the unperturbed individual waveguide modes. Consequently, when the unperturbed modal solutions for the individual waveguides are known, the fields of the coupled waveguide system can be calculated.

The optical modes of the individual waveguides are a solution to the (Helmholtz) wave equation that is associated with Maxwell's equations. In principle, one should take into account the complete two-dimensional (2-D) field pattern over the cross section of the waveguide. However, in good approximation, the field $\mathbf{E}(x,y)$ can be written as $\mathbf{E}(x)\mathbf{E}(y)$. In this approximation, it can be easily shown that if the waveguides have the same thickness (defined in the x direction; see Fig. 1), the coupling only depends on $\mathbf{E}(y)$. Using the correct boundary conditions, the transverse electric (TE) field pattern for the first even mode of the pump waveguide A is given by

$$\mathbf{E}^a(y) = C_a \begin{cases} \cos\!\left(k_y \frac{d}{2}\right) e^{-\alpha(y-d/2)}, & \text{if } y \geq +\frac{d}{2}\\ \cos(k_y y), & \text{if } |y| \leq \frac{d}{2}\\ \cos\!\left(k_y \frac{d}{2}\right) e^{+\alpha(y+d/2)}, & \text{if } y \leq -\frac{d}{2}\end{cases} \tag{3}$$

where k_y and α are determined from the eigenvalue equation (which is obtained by substituting (3) into the wave equation), C_a is a normalization constant, and d is the waveguide width. The above calculation can also be done to obtain the TE field of signal guide B.

With the modal fields of (3) as input for the coupled mode equations of (2), the modal amplitudes $a(z)$ and $b(z)$ can be calculated. If all pump power is launched into waveguide A at $z = 0$ $(a(0) = 1, b(0) = 0)$, the solution can be written as [7]

$$\begin{aligned}a(z) &= \left(\cos(\psi z) - i\,\frac{\Delta}{\psi}\sin(\psi z)\right)e^{i\phi z}\\ b(z) &= i\,\frac{k_{ba}}{\psi}\sin(\psi z)e^{i\phi z}\end{aligned} \tag{4}$$

where

$$\begin{aligned}\phi &= \frac{\gamma_a + \gamma_b}{2}\\ \psi &= \sqrt{\Delta^2 + k_{ab}k_{ba}}\\ \Delta &= \frac{\gamma_b - \gamma_a}{2}.\end{aligned} \tag{5}$$

We can now calculate the power inside signal guide B as

$$\begin{aligned}P(z) &= \frac{1}{2}\,\mathrm{Re}\int\!\!\int \mathbf{E}\times\mathbf{H}^*\cdot\hat{\mathbf{z}}\,dx\,dy\\ &= |a(z)|^2 + |b(z)|^2\\ &\quad + \mathrm{Re}[a(z)b^*(z)C_{ba} + b(z)a^*(z)C_{ab}]\end{aligned} \tag{6}$$

where the cross-overlap integrals C_{ab} and C_{ba} are given by

$$\begin{aligned}C_{ab} &= \frac{1}{2}\int\!\!\int \mathbf{E}^b\times\mathbf{H}^a\cdot\hat{\mathbf{z}}\,dx\,dy\\ C_{ba} &= \frac{1}{2}\int\!\!\int \mathbf{E}^a\times\mathbf{H}^b\cdot\hat{\mathbf{z}}\,dx\,dy\end{aligned} \tag{7}$$

and the integration is done over the cross section of the signal waveguide.

Using the same set of equations, it is also possible to calculate the coupling of the signal mode into the pump guide. In the present waveguide geometry (a broad single-mode signal guide and a narrow single-mode pump guide), this loss can be neglected.

III. Numerical Example

Using the equations derived in Section II, we can now calculate the effect of distributed coupling. As an example, we will consider a sensitized Nd^{3+}-doped polymer waveguide [2]. The Nd ions are incorporated in an organic complex that also contains an organic sensitizer group. In these complexes, 1340-nm emission of Nd is observed after excitation via the lissamine sensitizer. In this way, the Nd^{3+} ion can be excited efficiently, as a result of the strong absorption of the lissamine at the pump wavelength (515 nm). However, if the pump power is higher than the value needed for complete population inversion of the Nd, the excess pump light is still absorbed by the lissamine, leading to a reduced pumping efficiency. Therefore, the pump power should be kept below a certain limit over the length of the waveguide.

In this example, the pump power ($\lambda = 515$ nm) is coupled through a 0.5-μm wide waveguide parallel to a 1.8-μm wide signal ($\lambda = 1340$ nm) waveguide at a spacing between the centers of the waveguide of 2 μm. Both waveguides support only the fundamental mode. The real (n) and imaginary (k) part of the refractive index are listed in Table I for the two waveguides. In the present geometry, coupling from the signal waveguide into the pump waveguide is negligible, as the narrow pump guide does not support the 1340-nm mode. To avoid contamination of the pump waveguide with the sensitized Nd^{3+}- complex, the doped waveguide should be made first. This can be done by spincoating the doped layer onto the cladding layer in which the signal waveguide is etched. Next, the surplus of film is etched away, followed by the etching of the second trench for the pump waveguide. This can then be filled with the undoped polymer by a second spincoat step.

Fig. 2 shows the calculated intensity distribution of the pump over the length of the waveguide, using an input pump power of

TABLE I
WAVEGUIDE PARAMETERS OF THE COUPLED OPTICAL WAVEGUIDE SYSTEM AS USED IN THE CALCULATION

guide	λ(nm)	n_{guide}	k_{guide}	$n_{cladding}$	$k_{ladding}$
pump	515	1.5067	0	1.4616	0
	1340	1.4845	0	1.4465	0
signal	515	1.4973	0.0125	1.4616	0
	1340	1.4831	0	1.4465	0

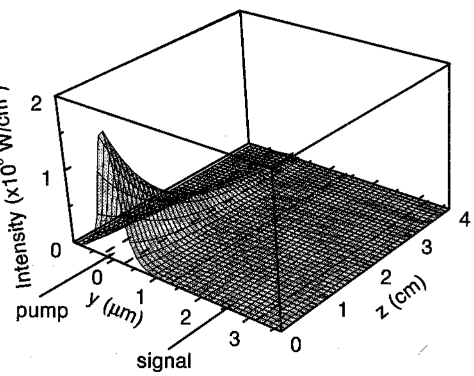

Fig. 2. Pump intensity in the waveguide structure as a function of distance z along the waveguide.

1 W. The intensity decrease in the nonabsorbing pump guide is entirely due to absorption of pump light coupled into the highly absorbing signal waveguide. In the present configuration, the pump power is almost completely absorbed after a distance of about 4 cm. The pump power in the signal guide as a function of the distance follows the same decreasing trend, because the coupling constant is constant over the length of the waveguides. It is not visible on the scale of Fig. 2 because the coupling constant is very small. It can be determined by integrating the data in Fig. 2 across the signal waveguide. The result is shown in Fig. 3. As can be seen, the power in the signal guide decreases from about 0.6 mW to almost zero over a distance of 4 cm.

The Nd^{3+}-level system can be described by a four-level system in which there is no minimum pump power required for optical gain. The differential gain along the amplifier is calculated using the known rate equations for the Nd^{3+}-level system, which are given in Appendix B, and the pump power as a function of distance along the guide calculated above. The result is shown in the inset of Fig. 3. Note that even with a pump power as low as 0.6 mW at the beginning of the signal guide, the differential gain is still reasonably high (~1.6 dB/cm). The total optical gain for this waveguide amplifier is given by

$$\text{gain(dB)} = 4.34 \times \eta \times \left(\int_0^L \sigma_{\text{se}} N f(z)\, dz \right) \tag{8}$$

where $\sigma_{\text{se}} = 1 \times 10^{-20}$ cm^2 is the cross section for stimulated emission at 1340 nm [8]–[10], $N = 5 \times 10^{19}$ cm^{-3} is the Nd^{3+} concentration, $f(z)$ is the fraction of excited Nd (see Appendix B), L is the length of the waveguide, and $\eta = 78\%$ is the relative overlap between pump and signal mode in the signal waveguide. For the example given here, the total gain is calculated to be 1.6 dB for a 4-cm long waveguide amplifier. To show the effect of distributed coupling, the inset of Fig. 3 also includes the differential gain obtained by using conventional butt coupling at the same input pump power of 1 W. Note that all pump power is completely absorbed within the first 50 μm. The total gain for this case is only 0.005 dB. Note that we have not taken into account the intrinsic waveguide losses at 1340 nm (~0.2 dB/cm) [11].

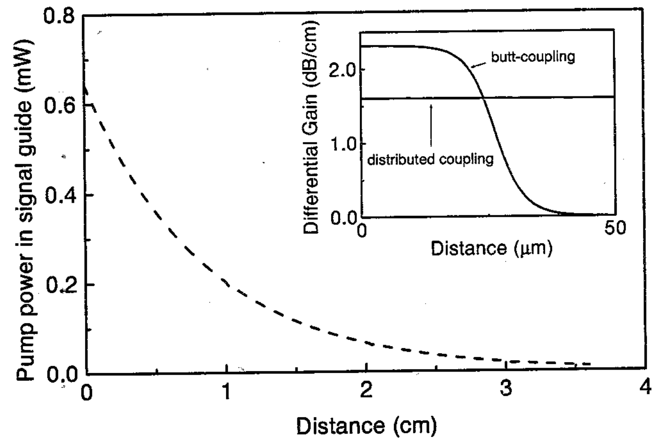

Fig. 3. Pump power in the signal guide as function of distance z in a sensitized Nd-doped polymer waveguide. The inset shows the calculated differential gain as a function of distance along the waveguide for a coupled waveguide system and a butt-coupled waveguide. The input power in the pump waveguide is 1 W, in both cases.

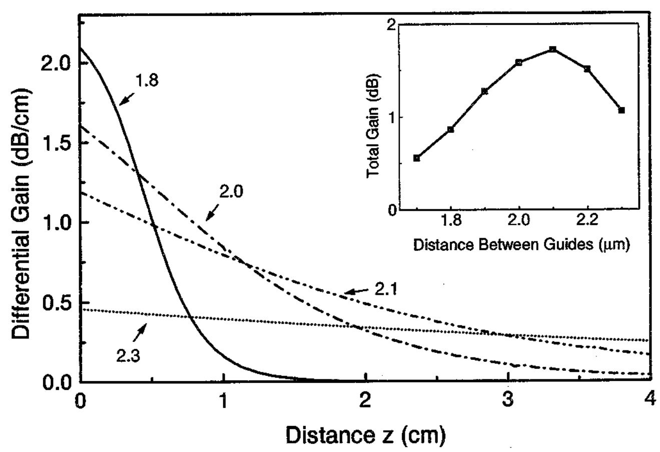

Fig. 4. Differential gain over the length of the waveguide, plotted for different separation between the waveguides. The numbers in the plot indicate the waveguide separation in micrometers. The inset shows the total gain for 4-cm long pump and signal waveguides as a function of the waveguide separation.

Fig. 4 shows the effect of the distance between two parallel 4-cm long waveguides on the differential gain. If the distance between the waveguides decreases, the coupling becomes stronger as more pump power will be coupled into the signal guide. This results in a higher differential gain at the beginning of the signal guide, but the pump power will be consumed more rapidly. Besides that, the pump power at the beginning of the waveguide is higher than the pump power for maximum amplification, resulting in pump losses. As a result, the total integrated optical gain will be lower. This can be seen in the

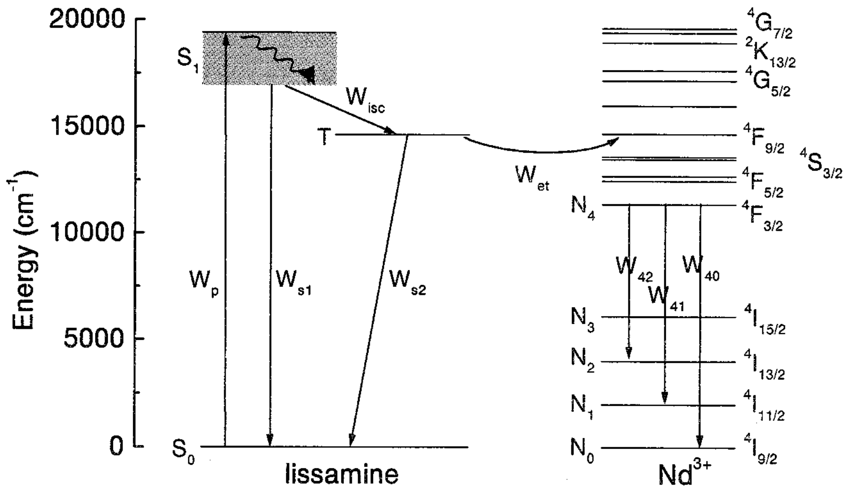

Fig. 5. Schematic energy level diagram of the Ls–Nd system. The different rate constants W_i used in the calculations are indicated.

TABLE II
VALUES FOR THE DIFFERENT RATES USED IN THE OPTICAL GAIN CALCULATION. $P(W)$ IS THE PUMP POWER IN THE SIGNAL GUIDE

rate	W_p (s^{-1})	W_{s1} (s^{-1})	W_{s2} (s^{-1})	W_{isc} (s^{-1})	W_{et} (s^{-1})	W_{40} (s^{-1})
value	5×10^9 P(W)	4×10^8	10^4	4.3×10^8	10^8	10^6

inset of Fig. 4, which shows the total integrated optical gain for a 4-cm long waveguide coupler as a function of the distance between the waveguides.

For a larger separation between the waveguides, the coupling is smaller, less pump power is coupled into the signal guide, and the differential gain is lower. In this configuration the total integrated optical gain is lower, but not all pump power is consumed. If the waveguide coupler is made longer, such that all pump power is used, the total integrated optical gain will be similar as for the 4-cm long coupler with the optimum separation of 2.1 μm between the guides.

IV. CONCLUSION

We have introduced an optical waveguide system, consisting of two closely spaced parallel waveguides, that can be used to optimize the pumping of planar waveguide amplifiers. The interaction between the two waveguides is calculated using CMT for nonidentical waveguides. It is shown that light coupled into the pump guide will gradually couple to the signal guide, resulting in a more efficient power distribution along the signal guide. Calculations on a sensitized Nd^{3+}-doped polymer waveguide system show that, using a butt-coupled waveguide, the total optical gain is 0.005 dB, whereas an optical gain of 1.6 dB is possible using a coupled-waveguide system (1-W input pump power). This clearly shows the advantage of the coupled waveguide system over the conventional butt coupling.

APPENDIX A

Equation (A1), shown at the bottom of the page, follows from the reciprocity theorem [6] with the conventional propagation constant β and coupling constant K_{ab}, and K_{ba} given by

$$\begin{aligned}\beta_{a,b} &= \frac{2\pi(n_{a,b}+k_{a,b})}{\lambda}\\ K_{ab} &= \frac{\omega}{4}\int\int \varepsilon^b(x,y)\left[E_t^a\cdot E_t^b - E_z^a\cdot E_z^b\right]\,dx\,dy\\ K_{ba} &= \frac{\omega}{4}\int\int \varepsilon^a(x,y)\left[E_t^b\cdot E_t^a - E_z^b\cdot E_z^a\right]\,dx\,dy\end{aligned} \tag{A2}$$

$$\left.\begin{aligned}\gamma_a &= \beta_a + \frac{K_{aa}-CK_{ba}}{1-C^2}\\ \gamma_b &= \beta_b + \frac{K_{bb}-CK_{ab}}{1-C^2}\end{aligned}\right\}\ \text{(modified propagation constants)}$$
$$\left.\begin{aligned}k_{ab} &= \frac{K_{ab}-CK_{bb}}{1-C^2}\\ k_{ba} &= \frac{K_{ba}-CK_{aa}}{1-C^2}\end{aligned}\right\}\ \text{(modified coupling constants)}$$
$$C = (C_{ab}+C_{ba})/2. \tag{A1}$$

where $\varepsilon^{a,b}(x,y) = \varepsilon(x,y) - \varepsilon^{a,b}(x,y)$.

Here, $n_{a,b}$ is the real part of the refractive index, $k_{a,b}$ is the imaginary part of the refractive index, $\varepsilon(x,y)$ is the permittivity function for the complete waveguide system, and $\varepsilon^{a,b}(x,y)$ is the permittivity function for the isolated waveguides A and B.

APPENDIX B

Fig. 5 shows the schematic energy level diagram for the lissamine–neodymium system. The lissamine is excited from the singlet ground state (S_0) into the excited singlet state (S_1) at a pump rate W_p, after which it can decay back to the ground state at a rate W_{s1}, or to the triplet state (T) via intersystem crossing at a rate W_{isc}. From the triplet state, it can then decay to the ground state radiatively at a rate W_{s2}, or nonradiatively by transferring its energy to the neodymium ion via Dexter energy transfer at a rate W_{et}. After the energy transfer process, the neodymium will be in the $^4\mathrm{F}_{9/2}$ and $^4\mathrm{S}_{3/2}$ level, from which it decays rapidly to the luminescent $^4\mathrm{F}_{3/2}$ state. We assume that the decay between adjacent levels is very fast, so that effectively the neodymium is excited directly into the $^4\mathrm{F}_{3/2}$ level (N_4). We also assume rapid decay from the N_1, and N_2 levels to the ground state. The rate equations can then be written as

$$\begin{aligned}
\frac{dS_0}{dt} &= -W_p S_0 + W_{s1} S_1 + W_{s2} T + W_{\mathrm{et}} T N_0 \\
\frac{dS_1}{dt} &= +W_p S_0 - W_{s1} S_1 - W_{\mathrm{isc}} S_1 \\
\frac{dT}{dt} &= +W_{\mathrm{isc1}} S_1 - W_{s2} T - W_{\mathrm{et}} T N_0 \\
\frac{dN_0}{dt} &= -W_{\mathrm{et}} T N_0 + W_{40} N_4 \\
\frac{dN_4}{dt} &= +W_{\mathrm{et}} T N_0 - W_{40} N_4
\end{aligned} \tag{B1}$$

The Nd population in N_4 is derived by solving these rate equations for the steady state. The total concentration of lissamine is equal to the Nd concentration, i.e., $S_0 + S_1 + T = N_0 + N_4 = N$. The fraction of excited Nd is given by $f = N_4/N$. The values of the different rate constants are given in Table II and have been derived from spectroscopic measurements [2], except for W_{et}, which is estimated from oxygen-quenching experiments [12], and W_{s2}, which is an estimate based on typical triplet-state lifetimes.

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