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A Beam Propagation Method for Analysis of Er-doped Planar Devices

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Abstract: A new method based on beam propagation method and rate equations is presented to calculate the gain and the output signals. Complex atomic susceptibility is applied when considering an equivalent refractive index to replace the effect of excited Er^{3+}. This refractive index is then used in BPM. The method is applied for an Er-doped splitter and it seems to be a powerful tool for Erbium-doped planar devices analysis.

Key words: Integrated optic, Er-doped and Optical Amplifiers.

1 Introduction

Recently Er^{3+} doped glass waveguide amplifiers have received a great deal of attention due to their potential for reducing cost and size and possibility for integration [1-4]. Er-doped glasses can be used to fabricate loss less or active devices. Planar loss-less splitters at 1.55 mm pumped at 980 nm and fabricated in an Er-doped glass were demonstrated in [5]. The methods used for analysis of Er-doped, such as the one presented in [1-6], are only valid for straight channels. In this paper we present a novel method for analysis of Er-doped in planar devices. The method is based on a combination of BPM[1] and rate equations that can also be applied for other configurations of devices.

2 Combination of BPM and rate equations

Assume an Er-doped optical device, such as splitter. Pump at 980 nm wavelength and signal at 1550 nm wavelength are combined using optical multiplexer. Complex atomic susceptibility theory [5] can be applied when considering an equivalent refractive index to replace the effect of excited Er^{3+}. Let us assume an Er^{3+} doped optical device with permeability,

$\varepsilon(x, y, z)$ to $\varepsilon(x, y, z) = n^2(x, y, z)$.

Excited Er^{+3} will modify the relative permeability from $\varepsilon(x, y, z)$ to:

$$\bar{\varepsilon}_l = n^2 + \chi_l(\omega) = n^2 + \chi_l^{'}(\omega) + j\chi_l^{''}(\omega) \quad (1)$$

For pump or signal wavelength (l = *pump* or $l = signal$). This relative permeability has the positive imaginary part representing optical gain or negative imaginary absorption loss:

$$\overline{\varepsilon_l}(\omega, x, y, z) = \varepsilon_l^{'} + j\varepsilon_l^{''}$$
$$\varepsilon_l^{''}(\omega, x, y, z) = \chi_l^{''}(\omega, x, y, z) \quad (2)$$

Where $\varepsilon_l^{''}$ is given by [5]:

[1] Beam Propagation Method

$$\varepsilon_l^{"} = \frac{n(x,y,z)c}{\omega_l} g_l \qquad (3)$$

The parameter c represents the velocity of light in vacuum and ω_l is the pump or the signal angular frequency. Optical gain, g_l, at pump and signal wavelength are given by :

$$g_{signal} = \sigma_{e21} N_2 - \sigma_{a12} N_1$$

$$g_{pump} = \sigma_{e31} N_3 - \sigma_{a13} N_1 \qquad (4)$$

where the parameters, N_1, N_2 and N_3 are population densities in the ground state, metastable level and pump level (see Fig. 1) respectively and $\sigma_{e\,ij}$ and $\sigma_{a\,ji}$ are emission and absorption cross section between i , j levels.

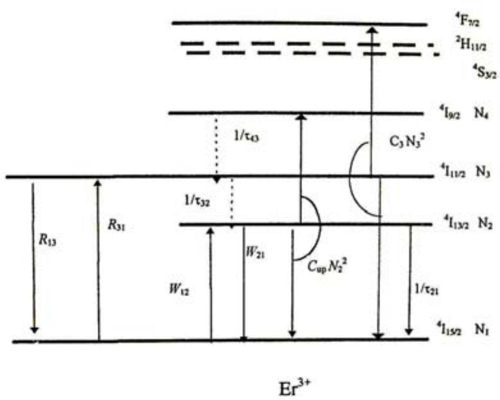

Fig.1 Energy level transitions for Er3+. Up conversion at pump level and signal level have been shown.

Population densities, $N_i(x,y,z)$, depend on the intensity of the pump and the signal at (x,y,z) through the rate equations. Here we assume the amplified spontaneous emissions (ASE)[1] are very smaller than the pump and signal powers. Therefore, ASE power is neglected in the rate equations. The real part complex atomic susceptibility, $\chi_l^{'}(\omega,x,y,z)$, is given by Hilbert transform in frequency domain through the Kramers-Kronig relation [7]. The real part of relative permeability, $\chi_1^{'}$, is very smaller than permeability of device, $\varepsilon(x,y,z)$. It is an important factor for dispersion of short pulses passed through the Er-doped device. But in steady state, the real part can be omitted.

A scalar BPM along z can be presented using these equivalent relative permeabilities. A time dependence of $\exp(j\,\omega_l\,t)$ has been assumed. Assume that

$$\tilde{E}_l(x,y,z) = E_l(x,y,z)\exp(-jk_l n_o z)$$

$$l = pump \quad \text{or} \quad l = signal \qquad (5)$$

where n_0 is a reference refractive index, k_1 is the wave number in the vacuum at the signal and the pump wavelengths, that $E_l(x,y,z)$ and $\tilde{E}_l(x,y,z)$ are main polarization component of electric field and its slowly varying envelope, respectively.

If the refractive index varies slowly along z, the scalar Helmolthz equation can be reduced to the paraxial wave equation which is [8, 9]:

$$\frac{\partial}{\partial z}\tilde{E}_l(x,y,z) = -j\hat{H}_l\,\tilde{E}_l$$

$$l = pump\ ,\ l = signal \qquad (6\text{-a})$$

$$\hat{H}_l = \frac{1}{2n_0 k_l}\left[\nabla_t^2 + k_l^2\left(\bar{\varepsilon}_1 - n_0^2\right)\right] \quad (6\text{-b})$$

At the point z_0 , the electric fields are known. One can also calculate the population densities by rate equations and find the equivalent relative permeability, $\overline{\varepsilon_l}$, at z_0. Then, one proceeds to obtain the electric field at $z_0 + \Delta z$ using Eq.(6). This process continues along the device. Carried power by

[1] Amplified Spontaneous Emissions

fundamental mode in output channel at $z = L$ can be calculated by overlapping integral:

$$P_{out}(z = L) = \left| \iint \tilde{E}_l(x, y, z = L) E_l^{fun}(x, y) dxdy \right|^2 \quad (7)$$

where $E_l^{fun}(x, y)$ is normalized electric field of fundamental mode in output channels.

3 Special case: straight channel waveguide

The present technique can be applied to analyze of single mode straight channel waveguide with refractive index, $n(x, y)$. The electromagnetic fields of modes in a wave guiding structure exhibit completeness as well as orthogonality and, therefore a system of complete orthogonal functions. The envelope of electric field, $\tilde{E}_l(x, y, z)$ can be written as:

$$\tilde{E}(x, y, z) = \sum_{\nu} A_{\nu}(z) E_{\nu}(x, y) \quad (8)$$

where $E_{\nu}(x, y)$ and $A_{\nu}(z)$ are normalized electric field and the coefficient of mode labeled by ν, respectively (Here we have deleted the l index, but all of following equations are satisfied at pump and signal wavelengths). We assume that channel waveguide is single mode, therefore the propagation constant (β_{ν}) of the mode labeled by $\nu = 1$ is real and other modes have pure imaginary index of fundamental mode $(\nu = 1)$. Substituting equation (6) and multiplying by $E_{\mu}(x, y)$ and integration over xy-plane yields:

$$\frac{d}{dz} A_l(z) = \frac{\Gamma}{2} A_l(z)$$

$$\Gamma(z) = \iint \left(\frac{k\varepsilon''}{n_0} + \frac{jk\chi'}{n_0} \right) |E|^2 dxdy \quad (9)$$

where $A_l(z)$ is the amplitude of fundamental mode. The power of fundamental mode, $P_l(z) = |A_l(z)|^2$ satisfies the following equation:

$$\frac{d}{dz} P_l(z) = \gamma(z) P_l(z) \quad (10)$$

where $\gamma(z)$ is real part of $\Gamma(z)$. The last equation is propagation equation that has also been described in [1, 6].

4 Numerical examples

This method was applied to several cases. The parameters of the glass shown in table 1 are also presented in [6]. We used the finite difference method as in [8] for propagation operator explained in equation (6). For the simplification of the method, a 2-dimensioanl version was used $(\partial/\partial y = 0)$. Therefore the power of pump and signal are expressed in terms of mW per unit length of y direction. Channels are 2 μm width with 1.536 refractive index in core and 1.51 in cladding. The signal and pump wavelengths are 1.531 μm and 980 nm. In all of examples, the total device length is 9 mm, the input pump and signal powers are $10\, mW / 1\mu m$ y-direction and $10\, mW / 1\mu m$ y-direction respectively. The erbium ions are also doped in the all of glass space. The first example is a 9.0 mm straight (2-dimensional) waveguide.

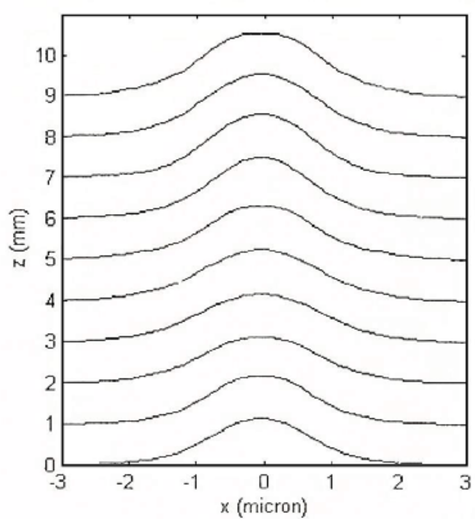

Fig.2 The slices of signal intensity (square of field) in a 9.0 mm straight Er-doped.

Figure.2 shows the normalized intensity of signal, $\left|E_s(x,z)\right|^2$, in several z slices. The input power in $(z=0)$ can be assumed as unity. By overlapping integral (7), the output signal power is 1.3 corresponding to 1.2 dB gain. Figure 3 also shows gain of this straight channel waveguide versus the pump power. As this figure shows there is good agreement between the present method and rigorous analysis in [1] and [6].

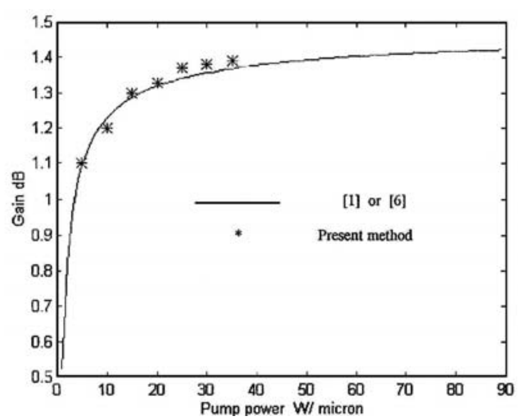

Fig.3 The comparing of calculated gain by present method with method in [1] or [2].

A 9.0 mm splitter is chosen as the second examples. The Splitter structure is illustrated in fig.3. The device is composed of two waveguides centered at $\pm x$ is:

$$x = \frac{R_t}{2}\left[1-\cos\left(\pi z' / S_t\right)\right] \qquad (11)$$

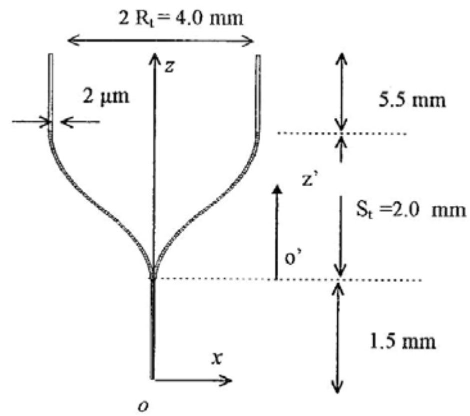

Fig.4 Illustrating the dimension of an Er-doped splitter. The channel is rectangular shape. The refractive index of core and cladding are 1.536 and 1.51 respectively. The sizes are not in scale.

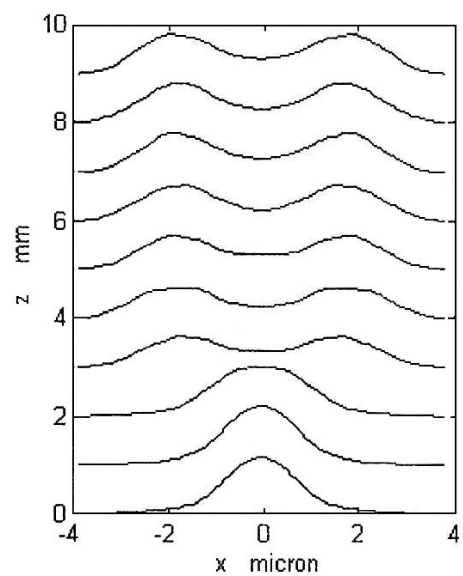

Fig.5 The slices of signal intensity (square of field) in a 9.0 mm splitter. The dimensions of splitter are shown in Fig. 4.

Er^{3+} concentration, N_{0Er}	$10\times10^{+26}\ ion/m^3$
Er^{3+} emission cross section, σ_{e21} (1.531 μm)	$5.41\times10^{-25}\ m^2$
Er^{3+} absorption cross section, σ_{e12} (1.531 μm)	$5.36\times10^{-25}\ m^2$
Er^{3+} emission cross section, σ_{e31} (980 nm)	0
Er^{3+} absorption cross section, σ_{a13} (980 nm)	$2.58\times10^{-25}\ m^2$
Er^{3+} emission life time, τ_{21}	$11ms$
Er^{3+} emission life time, τ_{21}	$1.0ns$

Table 1 Parameters of the glass, Al_2o_3 – Sio_2 [4]. Up conversion effects at pump and signal levels have been ignored in this reference.

The parameters R_t, S_t and z' are shown in Fig. 4. As Fig. 5 shows, an input signal is divided in two output signals. The addition of the output powers is about 1.61 times more than the input power. Two arms of the Splitter are very close together and distribution of pump power is not confined in the waveguides. The rigorous analysis in [1] and [6] can not be applied for this structure.

5 Conclusions

The design of the optical devices in Er-doped glass are required the field confinement of the pump and good overlapping between the pump and the signal intensity profiles. Also we should consider the other losses such as the radiation loss due to curvature. The presented BPM in section 2 considers all of the above. Therefore it will be a powerful tool for designing these types of optical devices. There are some disadvantages for this method. It is not able to calculate the ASE, noise figures and saturated gain when the ASE power are comparable to signal power.

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