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OPTICS AND SPECTROSCOPY

IMPROVEMENT OF A MODEL OF THE FIBER-OPTIC PARAMETRIC AMPLIFIER

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A method to take account for dispersion variations over the length of real fiber light guides in a model fiber-optic parametric amplifier is suggested. The theoretical and experimental amplification spectra of the parametric amplifier in a high nonlinearity fiber under continuous pumping conditions are compared.

The development of wide-band fiber-optic amplifiers is of practical importance due to the possibility of increasing the transmission capacity of fiber-optic communication lines. The performance of amplifiers built around rare-earth-doped fibers is restricted by the luminescence spectra of the active ions to the operation in the specified spectral range only. Raman amplifiers are not rigidly tied to the wavelength, but their amplification bandwidth is limited by the phonon spectrum.

Fiber-optic parametric amplifiers can in principle operate at any wavelength and can have a very wide amplification band. Their amplification bandwidth depends on the pumping power and the fiber nonlinearity and dispersion. The recent appearance of high nonlinearity fibers with Δn up to 0.04 [1] and low optical losses has made it possible to substantially reduce the necessary pumping power of fiber-optic parametric amplifiers and to operate them with continuous pumping a few hundreds of milliwatts in average power at an amplification bandwidth of a few tens of nanometers [2–4]. Fibers are now available with $\Delta n = 0.142$ that possess even higher nonlinearity [5]. Consequently, there is a possibility to materially increase the amplification bandwidth by optimally selecting the fiber and pumping parameters. An adequate mathematical model will allow one to find the necessary parameters.

To model an optical parametric amplifier implemented in the region of zero fiber dispersion, we have used the system of differential equations describing the interaction of waves in the amplifier that was obtained by the authors of [6, 7] from the coupled waves equation.

The fiber manufacturing accuracy is limited by the technological tolerance limits, hence, the actual parameters of a real fiber, especially the zero dispersion wavelength, can fluctuate along its length. This is especially true of high nonlinearity fibers with a high Δn and small diameter of the mode field. For a supermode high nonlinearity fiber with $\Delta n = 0.033$, diameter fluctuations by 0.12% cause the zero dispersion wavelength to vary by about ±6 nm in the spectral region of 1.5 μm, even without regard for the variations of the refractive index profile in the fiber blank. Random fluctuations of λ_0 along the fiber substantially reduce the optical parametric amplifier bandwidth. Thus, to achieve the closest agreement between the model and the experimental results, account should be taken of the λ_0 fluctuations along the fiber length. In the ideal case, one should know the exact magnitude of dispersion at every point of the fiber. However, the modern dispersion measurement techniques fail to provide these data with a necessary accuracy.

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When developing our model, we proceeded from the following assumptions. First, dispersion fluctuates in the fiber within the range determined from the fluctuation of the fiber diameter in drawing neglecting the variation of the refractive index profile in the fiber blank because its contribution to the variation of dispersion over a few hundreds of meters of fiber is small compared to the contribution from the fiber diameter fluctuations. The exact fiber diameter is recorded during the course of drawing. For the fiber sample under investigation, these data have been experimentally obtained. In our experiment, we used a fiber heavily doped with GeO_2, accounting for 30% of the molar mass in the core, the fiber diameter fluctuations in drawing amounted to ± 0.3 μm (which is equivalent to a $\pm$12-nm spread of the zero dispersion wavelength values). Second, since dispersion in the fiber assumes all of the values in the range from $\lambda_0 - \Delta\lambda$ to $\lambda_0 + \Delta\lambda$, one can find the length of the fiber section with zero dispersion for each particular wavelength from the total length of the section of fiber with the given dispersion. The entire length of the fiber is thus discretely divided into sections with specified zero dispersion wavelength values from the range $(\lambda_0 - \Delta\lambda, \lambda_0 + \Delta\lambda)$. The model then provides for the passage of the useful signal, the pumping radiation, the idler mode, and noise in a step-by-step manner through all of the sections with constant dispersion.

The lengths of the fiber sections with different dispersion curves and the order of passage of radiation through them should ideally be established experimentally by breaking the fiber into discrete sections (around 1 m in length) and measuring dispersion in these sections. However, it is difficult to do so in practice. Besides, after breaking the fiber into sections and then fusing them into a whole fiber again, the distribution of dispersion over the fiber length will differ from the original one, for the polarization mode dispersion changes.

In our model, the lengths of the fiber sections with discrete zero dispersion wavelengths are determined from the Gaussian distribution of an arbitrary quantity, identified with the significance of the contribution from a particular zero dispersion wavelength, in the pertinent fiber section in the range of variation of the zero dispersion wavelength throughout the piece of fiber being investigated.

Let the zero dispersion wavelength λ_0 be measured in a piece of fiber of length L. Assuming the spread of its values ranges from $\lambda_0 - \Delta\lambda$ to $\lambda_0 + \Delta\lambda$ (Fig. 1), we consider the Gaussian wavelength distribution of an arbitrary quantity. The central value of the distribution is at the point λ_0, while at the points $\lambda_0 - \Delta\lambda$ and $\lambda_0 + \Delta\lambda$ the value of the arbitrary quantity drops by a factor of e^2 relative to the maximal value. We take the area under the curve on the interval $(\lambda_0 - \Delta\lambda, \lambda_0 + \Delta\lambda)$ to be equal to unity. We divide this range into a finite number N of equal intervals. Let the length of the entire piece of fiber used correspond to the

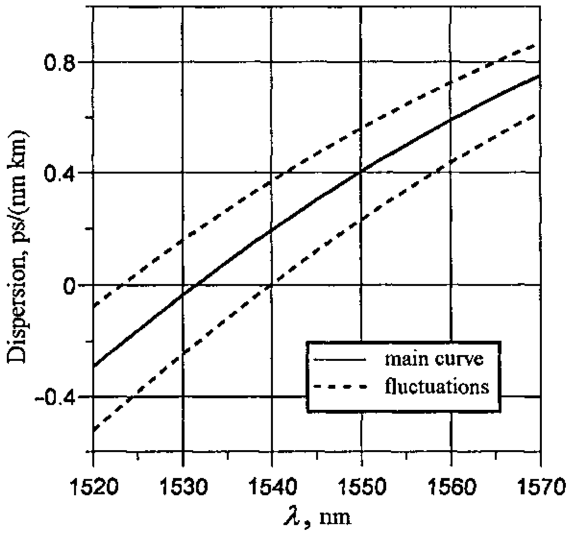

Fig. 1

Dispersion as a function of wavelength: main curve (solid) and curves corresponding to zero dispersion wavelength fluctuations (dashed).

area over the entire range and let the areas on the small intervals be proportional to the lengths of the fiber sections, $L_N = S_N L$.

Thus, we can determine the contribution each zero dispersion wavelength makes to the general amplification picture. The model is a system of series-connected fiber sections, each section having its own zero dispersion wavelength λ_0 and the length calculated from the Gaussian distribution. The sections are connected in the order of numbering increasing toward the center of the distribution, so that the fiber section corresponding to the central value of the zero dispersion wavelength is the last to transmit the signal, which provides for the greatest contribution from this wavelength value.

The experiment was staged by the scheme illustrated in Fig. 2. The source of pumping at a wavelength of 1543.8 nm is a tunable continuous-wave erbium-doped fiber laser, complete with an erbium-doped fiber amplifier (EDFA). The pumping radiation is coupled into a high nonlinearity fiber ($\Delta n = 0.033$, mode field diameter 3.5 μm at a wavelength of 1550 nm) 300 m in length and 1531 nm in zero dispersion wavelength, which serves as the active medium of our fiber-optic parametric amplifier. The output power spectrum of the optical parametric amplifier is observed by means of an optical spectrum analyzer.

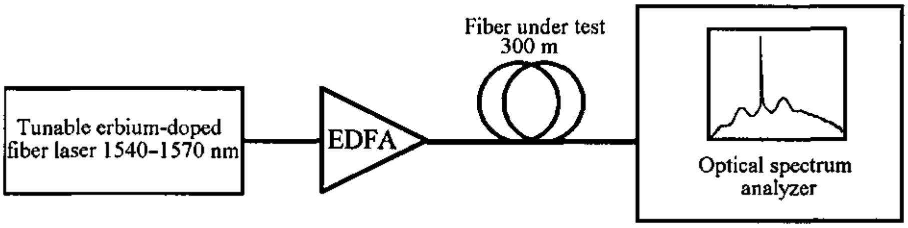

Fig. 2

Experimental scheme.

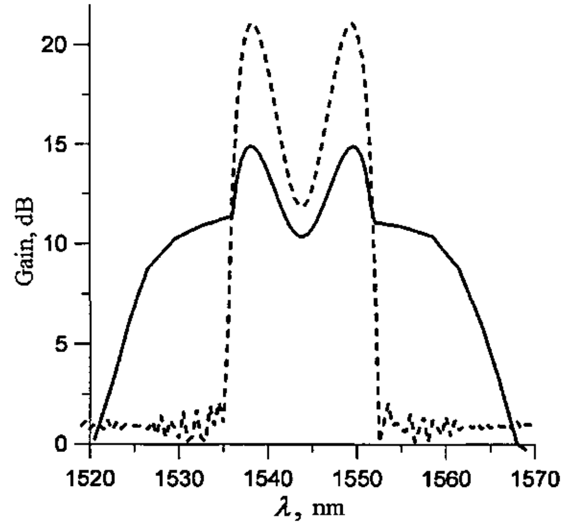

Fig. 3

Amplification spectrum: theoretical models constructed without (dashed line) and with (solid line) regard for dispersion wavelength fluctuations.

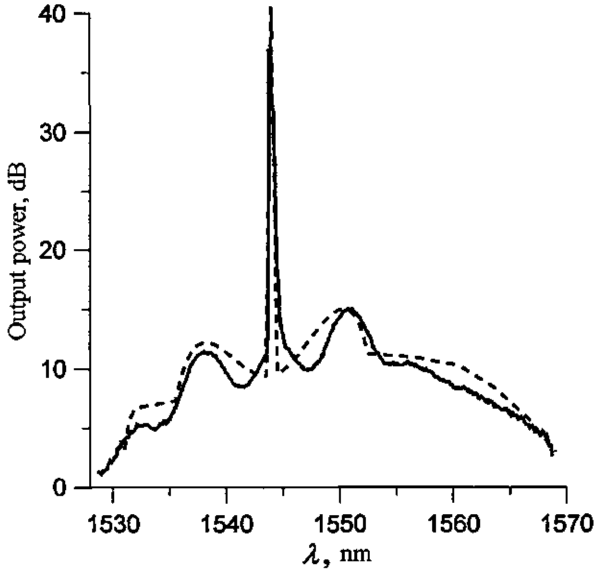

Fig. 4

Output power spectrum of amplified noise with residual pumping: experimental pattern (solid line) and theoretical model constructed with due regard for zero dispersion wavelength fluctuations (dashed line).

Figure 3 compares model amplification spectra at the parametric amplifier output constructed with and without regard for the fluctuation of λ_0. Figure 4 compares the experimental output power spectrum of amplified noise with residual pumping and the theoretical model allowing for the zero dispersion wavelength fluctuations. The asymmetry about the pumping wavelength results from the nonuniform distribution of noise produced by the erbium-doped fiber laser. In the theoretical amplification model (see Fig. 4), this asymmetry is taken into consideration by specifying a nonuniform erbium laser noise spectrum at the parametric amplifier input.

It can be seen from the above figures that the latter model agrees better with the experiment. In the former case, the two amplification peaks close to the pumping wavelength (in the range 1534–1553 nm) at which the signal amplification takes place are higher than in the latter case. In the system allowing for the fluctuation of the zero dispersion wavelength, noise increases on the spectrum periphery (1520–1534 nm and 1553–1570 nm) so that the signal is smeared. The parametric amplification peaks are lower than in the case where the zero dispersion wavelength fluctuation is neglected that is due to the development of increased noise in these regions as a result of energy transfer.

Consequently the theory allowing for the fluctuations of the zero dispersion wavelength provides a more precise model of an actual parametric amplifier than the theory of parametric amplification in a fiber with constant dispersion.

The optical parametric amplifier model presented in this work, which allows for the fluctuations of the zero dispersion wavelength, in the best way describes an actual amplifier. Such a model makes it possible to describe variations of the zero dispersion wavelength without breaking the fiber under study and directly measuring dispersion in its small sections. The contribution from each λ_0 value is identified with the length of the fiber section characterized by this value. These contributions correspond to a Gaussian wavelength distribution, which holds true only in the case of sufficiently long fiber. The model enables one to most adequately select the parameters necessary to obtain an optimal amplification spectrum of a fiber-optic parametric amplifier.

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