Output spectra and longitudinal mode structure of the Raman fiber laser

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Abstract: The shape of output spectrum and its internal structure arising from multiple longitudinal modes generating in the cascaded cavity of the two-stage phosphosilicate Raman fiber laser has been studied experimentally and theoretically. The mode structure has been analyzed using measurements of rf beat frequency spectra. An adequate analytical model has been developed and tested experimentally. It describes qualitative behavior and the observed spectral features for the first and the second Stokes components.

1. Introduction

Recently, an active development both in technology and numerical modeling of Raman fiber lasers (RFLs) resulted in optimisation of their performance and development of RFLs with high output power and efficiency almost at any wavelength in telecom range, applying conventional germanosilicate as well as phosphosilicate fibers [1,2]. At the same time, there are only few studies dedicated to the fundamental problems of the RFL operation, in particular, formation and shape of the output spectra and its broadening [3-7].

We have performed an experimental study of the spectral characteristics for the two-stage phosphosilicate Raman fiber laser in combination with the monitoring internal structure of the spectrum arising from multiple longitudinal modes of the RFL cavity formed by fiber Bragg gratings. Mode structure and their interactions have been studied by the technique of rf beating in the output power. An analytical model has been developed and tested experimentally. It adequately describes the features of the output spectra. The obtained results seem important both for understanding of the physical mechanisms of the generation and for the further optimization of the laser parameters and its applications.

2. Output spectra

The two-stage Raman fiber laser (RFL) (1,26/1.53 μm) pumped by Yb-fiber laser (1.08 μm) based on an 370-m long phosphosilicate fiber under study is shown in Fig.1. The cascaded cavities of the RFL are formed by pairs of the fiber Bragg gratings (FBGs) with reflectivity of 99% at their spectral maximum, except the output FBG with reflectivity of 42% at 1.52 μm (second Stokes wave wavelength). The spectral profiles were measured by optical spectrum analyzer (OSA), separately at each wavelength. The measured profile of the radiation at the 1.52μm has the form of narrow peak, the width of which grows if pump power increases, at the same time the output spectrum from the highly-reflective cavity (the output spectra of the first Stokes wave) is split in two components, Fig.2, (see also [1]).

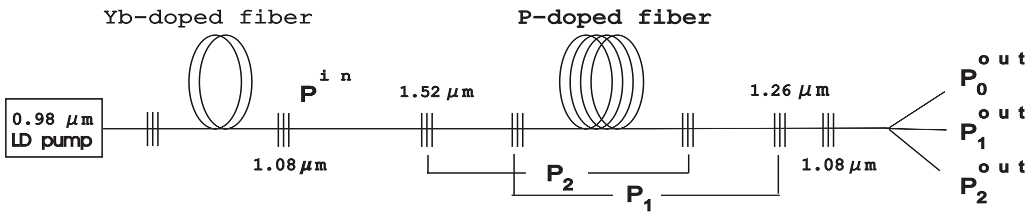


Fig.1. Experimental setup

To explain the shape of output spectra, we have analysed the well-known set of equations for stimulated Raman scattering, see e.g. [8], which describes the generation process in the two-stage RFL. Steady-state condition for generation (the saturated gain is equal to the sum of all losses) in the case of highly-reflective cavity with small total losses results in that the total power variation of the first Stokes wave along the fiber is small [9]. In this approximation and taking into account supposion of the independent generation of the Stokes wave at different frequencies (model of inhomogeneous gain saturation), one can derive an analytical expression for the spectral shape of the RFL output radiation for the first Stokes wave:

$$P_1^{out}(\lambda) = t_1(\lambda)\left(\frac{P_0^{in}/(2\lambda_1/\lambda_0)}{\alpha_1 L + \delta_1(\lambda)} - \frac{\lambda_0\alpha_0}{2\lambda_1 g_0}\right), \tag{1}$$

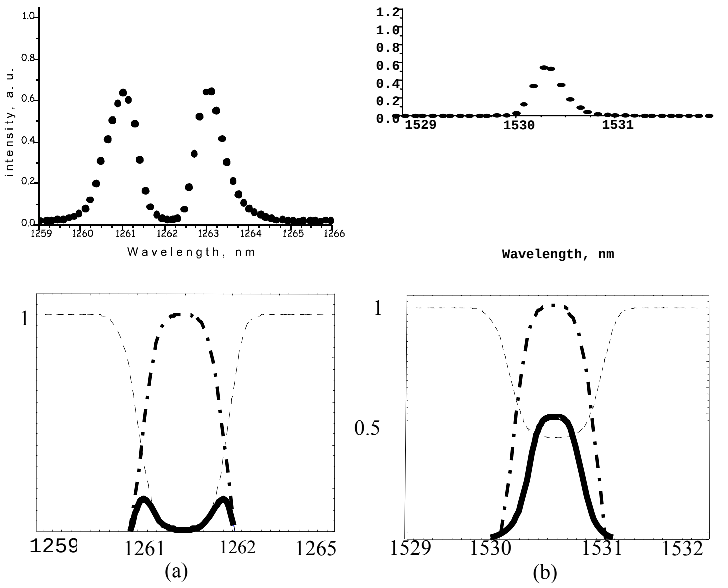
where P_0^{in} is the pump power, λ_0 and λ_1 are wavelengths, respectively, α_0 and α_1 are absorption coefficients of the pump wave and first Stokes wave, δ_1 includes lumped losses and losses for the transmission, $t_1(\lambda)$ is spectral dependence of transmission of the output FBG, g_0 is a raman gain coefficient, indexes 0 and 1 denote pump wave and first Stokes wave respectively. The expression in the large brackets corresponds to the intra-cavity power.

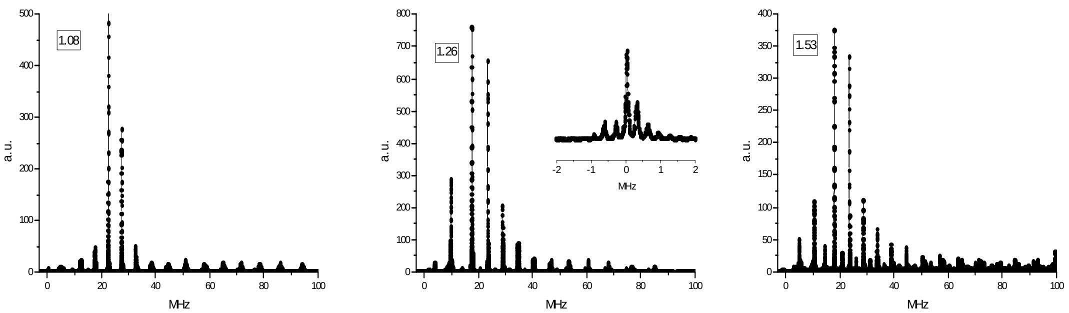
The data obtained from the analytical formulae (1) are shown in Fig.2 in the right column. One can see a good qualitative agreement between the model and the experiment. Let us mention that the model gives that the intra-cavity spectrum is not split (Fig.2, dotted line), that was also confirmed experimentally [7]. Under these circumstances, the effect of splitting has clear interpretation: the maximum power is achieved at the wavelength where the transmission coefficient is optimal.

At the same time, the model provides that if one uses an output grating with transmittance of ~50% instead of highly-reflective output FBG then the splitting disappears, because an optimum transmission is reached near the line center. That is the case of the second Stokes wave, and the experiment confirms the conclusion of the model, Fig. 2.

Fig. 2 (right). Output spectra of the first Stokes (a) and second Stokes (b) waves. Up – experimenal points; Down - theory: dashed line – FBG transmission spectra, dash-dots – intracavity spectra, solid line – output spectra.

Fig. 3 (down). Rf beat spectrum of the residual pump, the first and the second Stokes waves.





4. Mode structre

To clarify the mechanisms of the RFL output spectra formation, character of gain saturation while generating multiple longitudinal modes and the role of the mode interactions we have developed an experimental investigation of the rf beat spectrum by means of electric spectrum analyzer (ESA), separately for the first, second Stokes waves and residual pump power, Fig.3. One can see longitudinal cavity resonances for the Yb-laser separated by $c/2l \approx 6$MHz, which corresponds to the length of Yb-laser resonator of $l \approx 16$m. An additional HR FBG at 1.08μm placed near the exit of RFL (double-pass pump scheme is implemented) results in modulation of main peaks with the period of $c/2L \approx 280$kHz, which corresponds to the length of RFL resonator of

$L \approx 370$m. For the Stokes component we observe the same structure with the period of $c/2l \approx 6$MHz , each peak is modulated with the RFL cavity resonances at $c/2L \approx 280$kHz (see inset), and for the second Stokes wave the picture is similar. And what is important, that the mode structure of the first Stokes wave "copies" the mode structure of the multimode pump laser, and the mode structure of the second Stokes wave "copies" the mode structure of the first Stokes wave. Since the gain saturation of the Yb pump laser is inhomogeneous, the saturation of the Raman laser should be also inhomogeneous. This fact indicates that our suggestion of independent generation of the Stokes wave is correct for the first rough approximation.

Note, that the mode spectra has clear maximum, the shape of spectra changes with increasing pump power (these changes will be analyzed elsewhere) but the domination of $c/2l \approx 6$MHz resonances "translated" from pump laser remain to be the main feature of the RFL beat spectra, in contrast to previous study in the ring-cavity RFL [10], where only low-frequency resonances at frequency of c/L have been observed.

5. Conlusion

Both experimental and theoretical investigation of spectral characteristics of the RFL have been performed. A simple analytical model considering spectral broadening with increasing pump power has been developed. The model takes into account wavelength-dependent Raman gain saturation that results in the splitting of the output spectrum from the highly-reflective cavity because an optimum transmission is reached at the wings of the FBG reflection profile. Predictions of the model are tested by the experiment. The experimental study of the rf beat frequency spectrum of the RFL indicate that the suggestion of the independent generation of the Stokes wave at different frequencies (longitudinal modes) is enough as a first rough approximation. Interactions between modes lead to specific shape of the rf spectrum with maximum corresponding to higher-order peaks.

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