

# Raman Gain Properties of Optical Fibers with a High Content of Germanium and Standard Optical Fibers

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**Abstract**—Raman gain characteristics are measured for single-mode optical fibers with a high content of germanium and for commercially available optical fibers with shifted dispersion and a large effective core area. Optical fibers of these types were studied as active media for Raman fiber amplifiers at the wavelengths of 1.5 and 1.3  $\mu\text{m}$ . The maximum Raman gain was achieved for a fiber with a high content of germanium and was equal to 23.3 dB/(km W). Phosphorus–silicate 1.407- and 1.229  $\mu\text{m}$  Raman fiber lasers were employed as pump sources for Raman amplifiers.

## INTRODUCTION

The technology of wavelength-division multiplexing (WDM) has recently resulted in a considerable increase in the transmission capacity of fiber-optic communication systems up to several terabits per second [1]. The further improvement of the transmission capacity of such systems can be achieved through the expansion of the spectral range of WDM transmission toward the short-wavelength region. In this context, Raman fiber amplifiers (RFAs) hold much promise for telecommunication systems, since they can operate within the transparency window of optical fibers with a practically arbitrary wavelength. Therefore, it is of considerable interest to analyze the ways of optimizing the type of optical fibers for RFAs operating within different spectral ranges. In this study, we measured Raman gain parameters for standard and special optical fibers at two different wavelengths.

Single-mode optical fibers with a high content of germanium in the core offer much promise for discrete (concentrated) Raman fiber amplifiers. Such optical fibers allow the pump power and the length of the employed fiber segment to be minimized. On the other hand, it seems quite natural to consider standard communication optical fibers as possible elements for distributed Raman amplifiers. We have investigated gain properties of optical fibers of both types.

## EXPERIMENTAL SETUP AND METHODS OF MEASUREMENTS

The purpose of this study is to experimentally determine the Raman gain for the investigated optical fibers at the wavelengths of 1.5 and 1.3  $\mu\text{m}$ . The fiber Raman

gain coefficient (FRGC) is defined as a coefficient  $g_0$  that appears in the well-known equation governing the propagation of a signal in an optical fiber with Raman gain (e.g., see [2]):

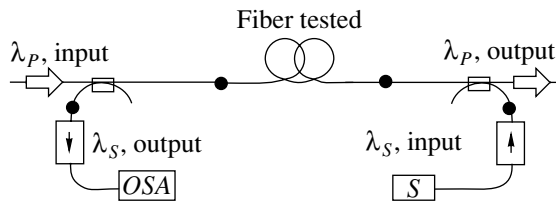
$$\frac{dP_S}{dz} = g_0 P_P P_S - \alpha_S P_S \quad (1)$$

where  $z$  is the coordinate measured along the optical fiber;  $P_S$  and  $P_P$  are the signal and pump powers (which generally may depend on  $z$ ), respectively; and  $\alpha_S$  is the magnitude of optical losses in the fiber at the signal wavelength  $\lambda_S$ .

Raman properties of optical fibers considerably depend on the radiation wavelength. Because of this reason, we measured parameters of optical fibers for two substantially different signal wavelengths:  $\lambda_S = 1500$  nm and  $\lambda_S = 1300$  nm. These wavelengths are of particular interest for expanding the spectral range of communication fiber-optic systems.

Each fiber was investigated as an active optical medium in two different schemes (for  $\lambda_S = 1500$  nm and  $\lambda_S = 1300$  nm) of a simple one-cascade Raman amplifier where the signal and the pump may propagate either in opposite directions (see Fig. 1) or in the same direction. We have studied optical fibers of three types: (a) a nonzero-dispersion-shift fiber (NZDSF), (b) a large-effective-core-area fiber (LEAF, the G.655 standard), and (c) a specially designed optical fiber with a high content of  $\text{GeO}_2$  in the core (23 mol.% of  $\text{GeO}_2$ , which corresponds to the difference in the refractive indices between the core and the cladding equal to  $\Delta n = 0.031$ ). The same segments of fibers were employed to perform measurements at both wavelengths.

Two continuous-wave Raman fiber lasers (RFLs) based on phosphorus–silicate fibers were used to pump



**Fig. 1.** Experimental setup for measuring the Raman gain in optical fibers where the signal and the pump propagate in opposite directions:  $S$ , source of the signal and OSA, optical spectrum analyzer. Rectangles with arrows indicate optical decouplers.

Raman amplifiers. These Raman lasers were pumped, in their turn, by radiation of neodymium lasers based on dual-cladding fibers. The RFL generating radiation with a wavelength of 1407 nm [3] was employed as a pump source for the 1500-nm amplifier, while the RFL generating 1229-nm radiation [4] pumped the 1300-nm amplifier.

Three methods were used to determine the FRGC for each of the fibers under study.

A single-mode laser diode was used as a source of the signal  $S$  in the first case (Fig. 1). An optical spectrum analyzer was employed to determine the small-signal gain  $G$  of the optical amplifier for a certain pumping level. Then, the quantity  $g_0$  was calculated in accordance with the formula

$$g_0 = \frac{G}{L_{\text{eff}} P_{p0}} \quad (2)$$

where

$$L_{\text{eff}} = \frac{(1 - \exp(-\alpha_p L))}{\alpha_p} \quad (3)$$

This procedure was used to determine the quantity  $g_0$  for different wavelengths corresponding to the wavelengths of radiation produced by the employed laser diodes.

In the second case, a broadband luminescence semiconductor diode was employed as a source of the signal  $S$ . The gain  $G$  of the optical amplifier was determined in this regime for all the wavelengths within the luminescence band of the semiconductor diode. Then, the quantity  $g_0$  within this frequency range was calculated with the use of Eqs. (2) and (3).

Finally, the specific feature of the third method for determining the quantity  $g_0$  was that the scheme of measurements shown in Fig. 1 did not involve any source of the signal  $S$ , and radiation resulting from the spontaneous Raman scattering of the pump in the fiber under study was, in fact, used as a source of the signal. It is much more complicated to calculate the quantity  $g_0$  in this case, since the source of the signal is distributed along the fiber length. However, the main advantage of this approach is that the measurement of the FRGC for any fiber within the entire band of Raman luminescence of this fiber does not require special sources of signal

emission. Therefore, we will substantiate this method in a more detailed way. For the sake of definiteness, we will consider the case when radiation emitted through a Raman process propagates in the direction of pump radiation. The regime when Raman-scattered radiation propagates in the direction opposite of the direction of pump radiation can be considered in a similar way.

If we can neglect pump depletion in the fiber (the regime of a small signal), then the power of Raman-scattered radiation  $P(z)$  at some wavelength  $\lambda$  propagating in the same direction as pump radiation can be found at the point of the fiber with a coordinate  $z$  with the use of the following equation:

$$\frac{dP(z)}{dz} = g_0 P_{p0} \exp(-\alpha_p z) P(z) - \alpha_s P(z) + A P_{p0} \exp(-\alpha_p z) \quad (4)$$

This equation is similar to Eq. (1). The first term on the right-hand side of this equation describes the gain of scattered radiation due to stimulated Raman scattering. The second term governs the linear absorption of the Stokes component. Finally, the last, third term on the right-hand side of Eq. (4) includes spontaneous Raman scattering at the point  $z$  [such a term does not appear in Eq. (1)]. The quantity  $A$  stands for the proportionality coefficient, which is independent of the pump power (but which, obviously, depends on  $\lambda$ ). The specific form of this coefficient is of no importance in the case under consideration.

Importantly, Eq. (4) can be solved in quadratures. Solving this equation, we derive the following expression for the power density of amplified Raman scattering at the output of the fiber under study:

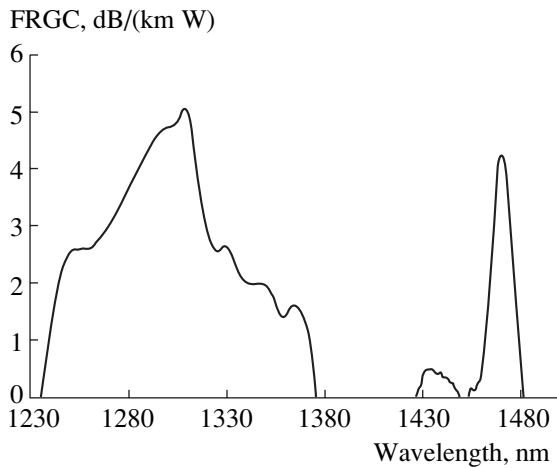
$$P_{\text{out}}(L) = \left[ A \int_0^L \frac{P_{p0} \exp(-\alpha_p z)}{\exp(F(z))} dz \right] \exp(F(L)) \quad (5)$$

where

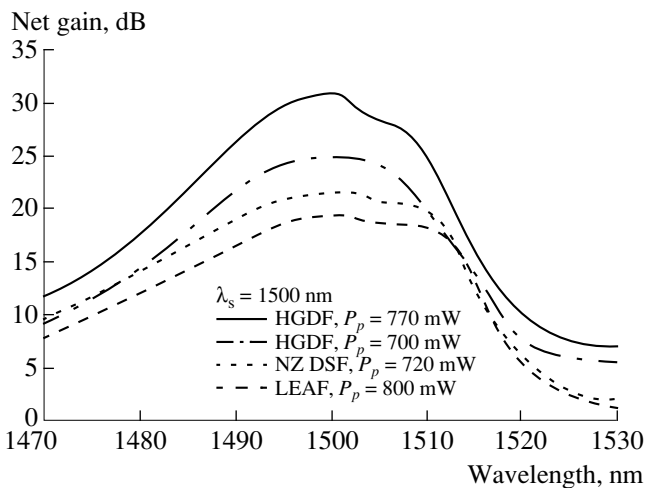
$$F(z) = \frac{1 - \exp(-\alpha_p z)}{\alpha_p} g_0 P_{p0} - \alpha_s z \quad (6)$$

The quantity  $P_{\text{out}}(L)$  substantially depends on the pump power  $P_{p0}$ . As can be seen from Eqs. (5) and (6), the ratio of the powers of amplified Raman scattering measured at the output of the fiber for two different pump powers is completely determined by  $g_0(\lambda)$ . The quantity  $A(\lambda)$ , which is involved as a factor in the right-hand side of Eq. (5), and all the frequency characteristics of couplers in the scheme of an optical amplifier have no influence on this ratio. Therefore, measuring the dependences of the power density of amplified Raman scattering  $P_{OSA1}(\lambda)$  and  $P_{OSA2}(\lambda)$  in the fiber for two different pump powers  $P_{p1}$  and  $P_{p2}$  and numerically solving the equation

$$\frac{P_{OSA1}(\lambda)}{P_{OSA2}(\lambda)} = \frac{P_{\text{out}}(P_{p1}, \lambda)}{P_{\text{out}}(P_{p2}, \lambda)} \quad (7)$$



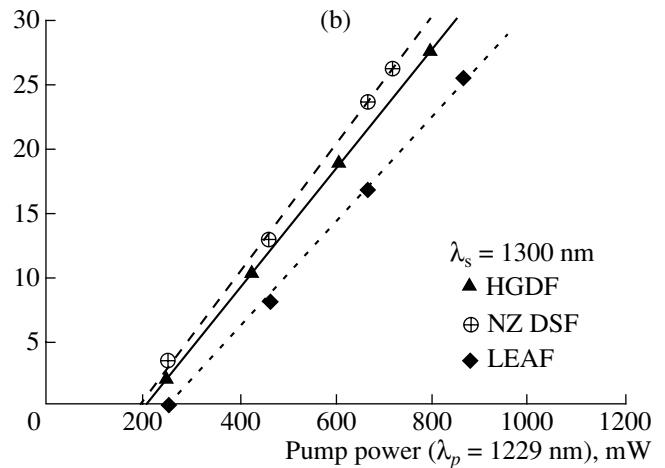
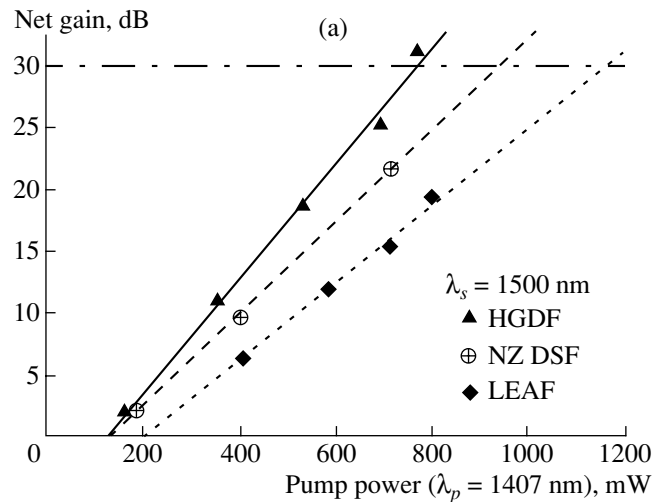
**Fig. 2.** The spectral dependence of the FRGC on the wavelength for a phosphorus-silicate single-mode optical fiber with a concentration of  $P_2O_5$  in the core of about 12 mol.% pumped by continuous-wave radiation with a wavelength of 1229 nm.



**Fig. 3.** Experimentally measured small-signal gains of Raman fiber amplifiers as functions of the wavelengths for different fibers and different values of the pump power.

for each  $g_0$  by algebraic methods (which considerably simplifies calculations), we can find the dependence  $g_0(\lambda)$ . Figure 2 presents the relevant dependence measured with the use of the above-described procedure within a broad wavelength range for the FRGC for a phosphorus-silicate optical fiber pumped by 1229-nm radiation.

All the three methods were used to measure the FRGCs for all the studied optical fibers in schemes with both forward and backward pumping. The results of these measurements agree well with each other. Therefore, in our further discussion, we do not specify the method used to obtain these data.



**Fig. 4.** Dependences of the gain on the pump power for Raman amplifiers using different fibers: (a)  $\lambda_p = 1407$  nm and (b)  $\lambda_p = 1229$  nm.

## RESULTS OF MEASUREMENTS

The spectral dependences of the gain for 1500-nm Raman fiber amplifiers are shown in Fig. 3. Analogous dependences for 1300-nm amplifiers display a similar behavior. The gains for all the studied optical fibers reach their maxima around the wavelengths corresponding to the Raman shift, which is approximately equal to  $440 \text{ cm}^{-1}$ . Figure 4 presents the maximum gains (for different wavelengths) as functions of the pump power.

The table summarizes the main results of our measurements. The maximum gains achieved with RFAs using optical fibers of a certain type are presented in the column A. The corresponding pump power coupled into the fiber in these measurements is given in parentheses. The column B presents the FRGCs  $g_0$  calculated with the use of the relevant experimental data. We emphasize that the quantities  $g_0$  given in the column B are related to the FRGCs at the wavelengths of 1500 and 1300 nm, which correspond to a maximum gain.

Parameters of Raman amplifiers and the studied germanium–silicate optical fibers

	A	B	C	D	E	F	G	H
	Net gain, dB (pump power, mW)	$g_0$ , dB/(km W)	$L_{\max}$ , km	Slope pump efficiency, dB/W	$\alpha_p$ , dB/km	$\alpha_s$ , dB/km	$L$ , km	$\alpha_p/g_0$ , mW
1500 mm								
HGDF	31.0(770)	18.9	7.75	46.0	1.46	1.06	5.5	77
NZDSF	21.6(719)	3.1	34.5	36.7	0.31	0.20	25	100
LEAF	18.4(804)	2.8	28.2	30.4	0.34	0.24	25	121
1300 mm								
HGDF	27.0(790)	23.3	5.2	45.9	2.03	1.63	5.5	87
NZDSF	26.2(715)	5.8	21.1	48.9	0.48	0.36	25	82
LEAF	22.3(860)	4.8	21.5	40.1	0.49	0.36	25	102

For each fiber, the maximum small-signal gain for a given pump power is achieved when the fiber length is equal to

$$L_{\max} = \frac{4.3}{\alpha_p} \ln \left( \frac{g_0 P_p}{\alpha_s} \right). \quad (8)$$

It is instructive to compare the values of  $L_{\max}$  presented in the column C with the real lengths  $L$  of optical fibers under study, which are given in the column G. The column D presents the slopes of the straight lines plotted in Figs. 3a and 3b. Finally, the column H presents the specific quality index of a fiber as an active medium for Raman amplification,  $\alpha_p/g_0$ . This index includes both optical losses and the Raman gain properties of a fiber. This parameter has a dimensionality of power. The lower is the quantity  $\alpha_p/g_0$ , the higher is the gain that can be achieved with a Raman amplifier using optical fibers of a given type.

The table demonstrates that, as one might expect, the smaller is the diameter of the fiber mode field, the higher is  $g_0$ . A strong dependence of  $g_0$  on the wavelength is observed for NZDSFs and LEAFs. This dependence approximately corresponds to the change in  $g_0$  due to wavelength dependences of the mode field diameter and the Raman gain of the bulk material in the fiber core and cladding. However, the fact that the wavelength dependence of  $g_0$  for HGDFs is very weak cannot be explained by the above-mentioned factors and requires further analysis.

An HGDF allowed us to achieve the best results within the wavelength range around 1500 nm. The maximum gain achieved for such fibers was equal to 31 dB for a pump power of 770 mW. Parameters of HGDF waveguides can be further improved through the development of the technology of fiber fabrication aimed at reducing optical losses. Although the values of  $g_0$  for NZDSF and LEAF waveguides were lower, these fibers displayed, due to the low magnitude of losses at the signal and pump wavelengths, a differential effi-

ciency of pump power conversion close to that typical of an HGDF. Note that the values of  $g_0$  measured in [5] within the range of 1540–1565 nm for fibers with shifted dispersion (the pump wavelength was around 1480 nm) agree well with the results of our measurements. HGDFs and NZDSFs have close parameters around 1300 nm. However, an important advantage of NZDSFs in this case is associated with a broader amplification band.

## CONCLUSION

A fiber with a high concentration of germanium in its core corresponding to  $\Delta n = 0.031$  ensures the higher gain within the range of wavelengths around 1500 nm than all the other studied fibers. The gain exceeding 30 dB was achieved with a one-cascade Raman amplifier using a fiber of this type with a pump power of 770 mW. In this study, we have demonstrated that high gains can be achieved at 1500 nm (20–25 dB with a pump power less than 1 W) with commercially available NZDSFs and fibers with a larger effective mode area pumped by a 1407-nm phosphorus–silicate fiber Raman laser. Parameters of the Raman gain in fibers at 1300 nm considerably differ from parameters of the Raman gain at 1500 nm. The maximum gain around 1300 nm was achieved with an optical fiber with shifted dispersion.

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