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A 1.65-μm fibre Raman amplifier

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***Abstract*. A fibre Raman amplifier operating at a wavelength of 1.65 μm is fabricated. A two-stage phosphosilicate fibre Raman converter of 1.53-μm radiation for pumping the Raman amplifier is designed and tested. The amplifier pumped by a phosphosilicate fibre Raman converter can operate with a maximum of the gain band ranging from 1.6 to 1.7 μm. A fibre with a core of a high (25 %) molecular content of GeO_2 serves as an active medium for the Raman amplifier. The gain obtained for different powers of the input signal is 22 – 25 dB. Our calculations show that the use of a standard telecommunication fibre (with a lower content of GeO_2) allows one to increase the gain in this scheme by reducing fibre splicing losses.**

Keywords: *Raman amplifier, Raman converter, highly doped fibre, gain.*

1. Introduction

Within decades, the transmission capacity of fibreoptic communication lines has been improved exclusively by increasing the signal transmission rate at a single wavelength. In recent years, however, the wavelength-division multiplexing (WDM), i.e., the transmission of signals at different wavelengths through a single fibre, has been used to considerably increase the data-transmission rate. The present-day quality of optical fibres enables the transmission of optical signals with wavelengths up to 1.7 μm due to sufficiently low optical losses in this spectral range. However, extending this technique to the long-wavelength range requires adequate optical amplifiers. The erbium-doped fibre amplifier operates at wavelengths shorter than 1.6 μm. To amplify signals with wavelengths longer than 1.6 μm, amplifiers based on stimulated Raman scattering can be used.

The working range of Raman amplifiers, in contrast to that of rare-earth fibre amplifiers, is not limited to the transparency band of silica fibres. For example, in germanium oxide, which is most frequently used as a dopant increasing the refractive index of the fibre core, as well as in silicon oxide, the Raman shift relative to the pump frequency is $\Delta\nu_R = 440\ cm^{-1}$. Thus, to amplify signals in the range from 1.6 to 1.7 μm in such fibres, 1.5 – 1.58-μm pump is necessary. Erbium – ytterbium-doped double-clad fibre lasers and Raman converters are capable of providing sufficiently powerful pump for such fibre amplifiers.

Amplifiers with a gain band covering the entire working wavelength range are required for WDM communication lines. To produce an efficient amplification in the 1.6 – 1.7-μm range (where erbium amplifiers are no longer efficient, while optical losses in fibres are still sufficiently low), it is necessary to pump the amplifier at several wavelengths simultaneously, because the width of Raman spectra in silica fibres usually does not exceed 50 nm. The working range of erbium – ytterbium-doped fibre lasers spans from 1.53 to 1.6 μm, which makes it possible to use these lasers to pump Raman amplifiers operating in the 1.65 – 1.7-μm range. On the other hand, fibre Raman converters can be used to amplify signals within the entire spectral range from 1.6 to 1.7 μm and even at longer wavelengths. Thus, either a combination of an erbium – ytterbium-doped fibre laser and a Raman converter or several fibre Raman converters working at different wavelengths can be used to pump amplifiers of 1.6 – 1.7-μm radiation.

In this context, Raman lasers or Raman converters attract much attention. Many works have been published on germanosilicate fibre Raman converters pumped by ytterbium or neodymium lasers [1, 2].

However, Raman oscillation at 1.53 μm in a germanosilicate fibre pumped by an ytterbium laser at 1.06 – 1.12 μm requires a seven-cascade Raman conversion, which complicates a cavity, gives rise to substantial optical losses, and makes the whole device rather expensive.

The design of the cavity of a Raman converter can be substantially simplified by using materials with Raman shifts greater than that of germanium oxide. In particular, phosphorous pentaoxide P_2O_5, with $\Delta\nu_R = 1300\ cm^{-1}$, is that kind of material. Optical fibres with a core doped by P_2O_5 and low optical losses [3], developed in recent years, open an opportunity to create efficient Raman converters [4].

In this work, we have developed and tested a fibre Raman amplifier operating at a wavelength of 1.65 μm, as well as a two-stage phosphosilicate fibre Raman converter, which was used to pump the amplifier. A fibre with a high content of germanium oxide in the core was employed as a gain medium in the Raman amplifier. However, our calculations show that the parameters of the Raman amplifier can be considerably improved by using a standard

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single-mode dispersion-shifted fibre (DSF). Such a fibre has a substantially lower gain with much lower splicing losses due to a greater size of the mode spot compared to a germanate fibre.

2. Experimental

A fibre Raman converter was pumped by a 1.089-μm double-cladding ytterbium–doped fibre laser (Fig. 1). The maximum output power of the laser was 5.2 W. The cavity of the Raman converter consisted of two pairs of Bragg gratings reflecting at the wavelengths of the first and second Stokes components, equal to 1.272 and 1.533 μm, respectively, as well as the grating reflecting at the pump wavelength. A fibre with a molecular content of P_2O_5 equal to 11 % and optical losses of about 1 dB km^{-1} was used as an active medium. With the present status of the phosphosilicate fibre production technology, this system provides optimal parameters [3]. The length of the phosphosilicate fibre was 250 m.

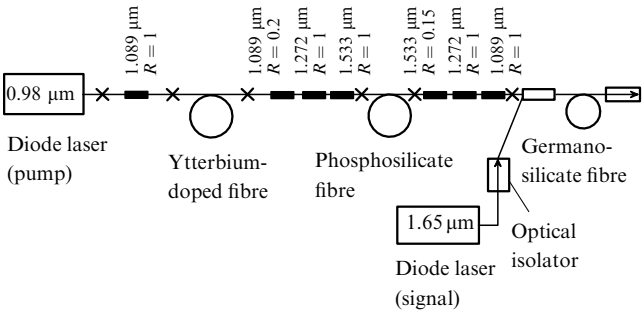

Figure 1. Schematic of the amplifier (crosses denote splicing junctions).

A diode laser with a fibre output was used as a source of a 1.65-μm signal to be amplified. The pump and signal beams were coupled into the amplifier through directional couplers. To prevent lasing in the cavity formed by the output end of the amplifier and the output mirror of the diode laser, we inserted two optical isolators into the scheme.

Two optical fibres (I and II) with a high content of GeO_2 in the core and similar characteristics (Table 1) were used in the experiments. The mode-field diameter of the fibre with the high content of germanium oxide substantially differed from that of the standard fibre used to make the directional coupler. This resulted in high splicing losses. The pump power coupled into the amplifying fibre was 800–900 mW.

3. Experimental results

The dependence of the Raman-converter output power on the pump power is shown in Fig. 2. The differential lasing efficiency is 52 %, and the quantum efficiency with 5.2-W pump is 56 %. The maximum output power of the Raman converter amounts to 2.1 W.

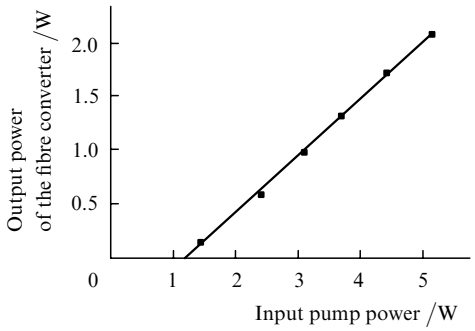

Figure 2. Output power of the fibre converter operating at 1.533 μm versus the input pump power.

Characteristics of the amplifier were measured for the input power of the signal P_{s0} equal to 5 and 220 μW (Fig. 3). For the power $P_{s0} = 220$ μW, we obtained a gain of 25 dB in a 7.2-km fibre I (Fig. 3a). Since the optical isolator partially transmitted 1.65-μm radiation in backward direction, the decrease of the signal power in the fibre I resulted in a spontaneous lasing in the cavity formed by the output end of the fibre and the output mirror of the diode laser. We, therefore, investigated amplification of a signal with a lower power using a fibre II with a smaller length (3.3 km), where the gain of more than 20 dB was achieved by amplifying a signal with the power $P_{s0} = 5$ μW (Fig. 3b).

4. Analysis of experimental results and numerical optimisation of a Raman amplifier

A substantial disadvantage of the created amplifiers are high losses related to the splicing of a germanosilicate fibre with the output of the directional coupler, which are caused by a large difference between the mode-field diameters. An increase in the mode-field diameter of a germanate fibre with a high content of GeO_2 (and, con-sequently, with a high refractive-index difference Δn between the core and the cladding) up to the mode-field diameter of a standard telecommunication fibre with a lower content of GeO_2 and

Table 1.

Fibre characteristics	Dispersion-shifted fibre (DSF)	Highly doped SiO_2/GeO_2 fibre	
		I	II
Optical losses α_s ($\lambda = 1.65$ μm)/dB km^{-1}	0.25	0.57	0.58
Optical losses α_p ($\lambda = 1.53$ μm)/dB km^{-1}	0.2	0.68	0.8
Fibre gain g_0/dB W^{-1} km^{-1}	2.3	8.8	10.5
Fibre length/km	1.0	7.2	3.329
Input signal power P_{s0}/μW	370	220	5
Losses due to splicing with a coupler α_w/dB	0.4	2.8	2.2
Mode-field diameter ($\lambda = 1.65$ μm)/μm	7.3	4.7	4.3

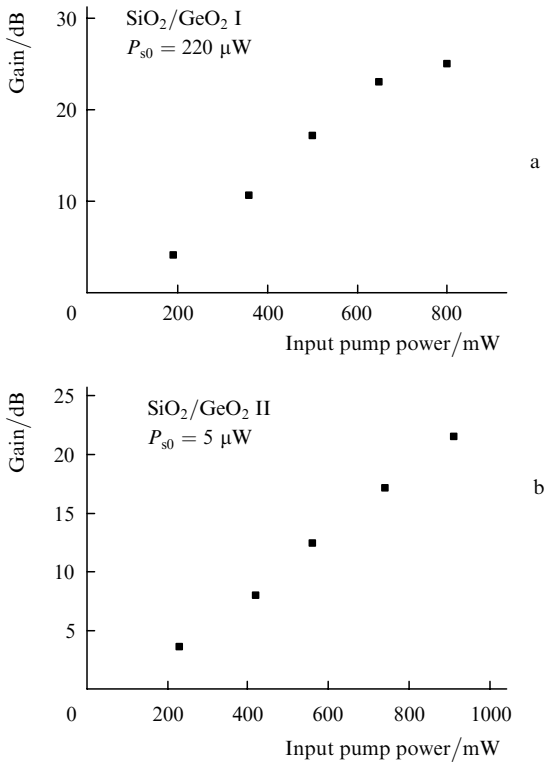

Figure 3. Gain of the Raman amplifier versus the input pump power for fibres of type I (a) and type II (b).

much lower Δn will shift the cutoff wavelength of the second mode of the germanate fibre beyond $\lambda > 1.65$ μm.

On the other hand, the standard fibre itself can be used to amplify the signal. This fibre has a lower gain, but permits the coupling of the entire pump power. With this idea in mind, we performed calculations, which allowed us to compare characteristics of a fibre Raman amplifier based on a fibre highly doped with germanium oxide and those of an amplifier based on a standard dispersion-shifted fibre (DSF).

The Raman amplifier is described by a set of four differential equations:

$$\frac{dP_p^{\pm}}{dz} = \mp\left[k_0 g_0 (P_s^+ + P_s^-)P_p^{\pm} + \alpha_p P_p \pm\right],$$
$$\frac{dP_s^{\pm}}{dz} = \pm\left[g_0 (P_p^+ + P_p^-)P_s^{\pm} - \alpha_s P_s^{\pm}\right] \quad (1)$$

with boundary conditions

$$P_p^+(0) = P_{p0},\ P_s^+(0) = P_{s0},$$
$$P_p^-(L) = P_p^+(L)R_{out}^p,\ P_s^-(L) = P_s^+(L)R_{out}^s, \quad (2)$$

where $P_p^+, P_p^-, P_s^+, P_s^-$ are the powers of the pump (p) and the signal (s) propagating in the forward (+) and backward (–) directions; z is the coordinate along the fibre; g_0 is the gain coefficient of the fibre; $k_0 = \lambda_s/\lambda_p$ is the ratio of the signal wavelength to the pump wavelength; α_p, α_s are optical losses at the wavelengths λ_p and λ_s; P_{p0}, P_{s0} are the pump and the signal powers at the input of the amplifier; and R_{out}^p, R_{out}^s are the reflection coefficients of output gratings at the pump and signal wavelengths.

Characteristics of fibres required for the calculation are summarised in Table 1. The gain coefficient g_0 of the fibre, appearing in (1), depends only on fibre properties and can be found from the solution of the set of equations (1) by using the measured values of the signal gain and the pump and signal powers at the input of the amplifier.

The gain g_0 for the fibres I and II was calculated using the data presented in Fig. 3. A 1-km fibre section was used to measure the gain in a DSF. When the maximum pump power coupled into the fibre was equal to 1.4 W and the input signal power was 0.37 mW, we obtained the signal gain equal to 2.9 dB. This allowed us to estimate the DSF fibre gain coefficient g_0 as 2.3 dB W^{-1} km^{-1}.

The calculations of characteristics of the amplifier included splicing losses (Table 1) and were carried out for the pump power at the output of the directional coupler equal to 1.5 W. The calculated values of the gain for the optimal length of the fibre are summarised in Table 2. It is important to note that the gain attainable with this scheme by using a standard DSF fibre exceeds the gain of the device based on the fibre with a high content of GeO_2. This is explained by high losses of the pump power at the splicing of the amplifying fibre with the directional coupler caused by a considerable difference in the mode-field diameters.

5. Conclusions

Thus, in this work we fabricated and tested a two-stage phosphosilicate fibre Raman converter operating at a wavelength of 1.53 μm, which is used to pump a Raman amplifier. The differential efficiency of the Raman converter is 52 %, with the maximum output power being equal to 2.1 W. A Raman amplifier operating at a wavelength of 1.65 μm was also developed and tested. For the input signal power of 220 μW, we obtained the gain equal to 25 dB. With an input power of 5 μW, the gain was 22 dB. A substantial disadvantage of this scheme is associated with coupling losses of pump power at the input of the amplifying fibre, which are caused by a considerable difference between the mode-field diameters of the fibres.

Amplifying characteristics of the standard DSF were also investigated. The results of these measurements were then used to theoretically optimise the Raman-amplifier scheme involving a highly doped (GeO_2) fibre and the standard DSF. The mode-field diameter in the latter fibre coincides with the mode-field diameter in the fibre

Table 2.

Fibre characteristics	Dispersion-shifted fibre (DSF)		Highly doped SiO_2/GeO_2 fibre	
			I	II
Input signal power P_{s0}/μW	5	220	220	5
Optimal length of a fibre/km	39.5	23.2	10.2	12.8
Gain G/dB	40.3	30.9	26.4	37.9

of the directional coupler, allowing one to couple the pump power into the amplifier with virtually no losses. Thus, the maximum gain, which can be achieved in the standard fibre, substantially exceeds the maximum gain in a highly doped fibre. It may reach the value of 40.3 dB for the signal power of 5 μW and the optimal length of 39.5 km, being equal to 30.9 dB for the signal power of 220 μW and the optimal length of 23.2 km.

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References

1. Grubb S.G., Erdogan T., Mizrahi Y., Strasser T., Cheung W.Y., Reed W.A., Lemaire P.J., Miller A.E., Kosinski S.G., Nykolak G., Becker P.C., Peckham D.W. *Proc. Opt. Amplifiers and Their Applications* (Brickenridge, USA, 1994, PD-3).
2. Dianov E.M., Fursa D.G., Abramov A.A., Belovolov M.I., Bubnov M.M., Shipulin A.V., Prokhorov A.M., Devyatykh G.G., Gur'yanov A.N., Khopin V.F. *Kvantovaya Elektron.,* **21**, 807 (1994) [*Quantum Electron.,* **24**, 749 (1994)].
3. Dianov E.M., Egorova O.N., Bubnov M.M., Bufetov I.A., Gur'anov A.N., Khopin V.F., Semjonov S.L., Shubin A.V. *Proc. SPIE Int. Soc. Opt. Eng.,* **4216**, 32 (2000).
4. Karpov V.I., Dianov E.M., Paramonov V.M., Medvedkov O.I., Bubnov M.M., Semyonov S.L., Vasiliev S.A., Protopopov V.N., Egorova O.N., Khopin V.F., Gur'yanov A.N., Machynskii M.P., Clements W.R.L. *Opt. Lett.,* **24**, 887 (1999).