PACS numbers: 42.81.Bm; 42.81.Qb; 42.65.Es
DOI: 10.1070/QE2014v044n11ABEH015623

Influence of pump wavelength and core size on stimulated Brillouin scattering spectra of acoustically antiguiding optical fibres

M.E. Likhachev, V.V. Alekseev, M.M. Bubnov, M.V. Yashkov, N.N. Vechkanov, A.N. Gur'yanov, N. Peyghambarian, V. Temyanko, J. Nagel

Abstract. **Optical fibres having an acoustically antiguiding structure produced by alumina doping of their core have been fabricated and investigated. The stimulated Brillouin scattering (SBS) spectra of the fibres have been measured and calculated theoretically. The results demonstrate that the shape of the SBS spectrum of the acoustically antiguiding fibres strongly depends on the pump wavelength, core size and dopant profile across the fibre. A considerable broadening of the SBS gain spectrum is only possible at certain guidance parameters of the fibre and a fixed operating wavelength.**

Keywords: *SBS, optical fibre, acoustically antiguiding structure.*

1. Introduction

High-power (up to tens of watts) narrow-band (less than 100 MHz in linewidth) laser sources are currently widely used in distributed sensors, spectroscopy and astronomical adaptive optics systems. A major factor that may limit their maximum output power is stimulated Brillouin scattering (SBS), which has the lowest threshold among the nonlinear effects and occurs at increased output powers of narrow-band lasers [1]. In Er- or Yb-doped fibre lasers and amplifiers, output powers of several tens of watts are usually not critical, because their large gain coefficient allows relatively short lengths of active fibres to be used. At the same time, if a desired source wavelength lies beyond the gain band of the rare-earth elements, SBS is a major problem. For example, fibres that are used in Raman lasers and amplifiers have a relatively small Raman gain coefficient, and considerable fibre lengths (hundreds of metres) are needed to obtain optical powers at a level of several watts [2]. SBS then rapidly becomes a predominant process, which limits the output power and efficiency of the devices in question.

A variety of approaches to suppressing SBS amplification in fibres have been proposed in order to overcome the existing limitations on the output power of single-frequency fibre lasers. The most widespread approach is to vary the acoustic properties (and, hence, the position of the SBS gain band) of the fibre along its length, which broadens the SBS spectrum and raises the SBS threshold of the fibre. In the simplest implementation of this approach, several fibres having different SBS spectra are connected in series by fusion splicing [3]. Other possibilities are to vary the refractive index profile along the length of the fibre via variable doping of its preform [4, 5] and to create a temperature gradient [6] or variable stress [7] along the length of the fibre. In a number of cases, all these methods are rather effective, but they are by no means always applicable (for example, in the case of short lengths of fibres or large mode field diameter fibres). Moreover, they are rather difficult to implement and cannot always be used in practice.

Because of this, recent years have seen increasing interest in SBS suppression by producing an acoustically 'antiguiding' structure [8, 9]. The main idea of this method is that the presence of an acoustic waveguide due to the difference between the speeds of acoustic waves in the core and cladding of a fibre leads to an increase in the time of interaction between an optical and an acoustic wave and, as a consequence, to narrowing of the SBS spectrum and lowering of the SBS threshold. That the SBS spectrum of single-mode fibres differs from that of bulk materials was first pointed out as early as 1979 [10], but a search for techniques to suppress this effect was begun comparatively recently. Among the dopants used in the fabrication of silica fibres, only alumina raises their optical refractive index and reduces their acoustic refractive index [11], thereby enabling one to create an acoustically 'antiguiding' structure. Indeed, in several reports experimental evidence has been presented that aluminosilicate core fibres have a higher SBS threshold than do germanosilicate core fibres [12, 13].

It is worth noting, however, that the effectiveness of the antiguiding approach is not quite obvious. For example, Zou et al. [14] experimentally investigated the SBS behaviour of fluorinated cladding/silica core fibres. Since the acoustic refractive index of a reflective fluorosilicate cladding exceeds that of undoped silica glass, such fibres also have an acoustically 'antiguiding' structure. At the same time, Zou et al. [14] found that the SBS threshold in the fluorinated cladding/silica core fibres did not exceed that in silica cladding/germanosilicate core fibres. Therefore, the presence of an antiguiding profile is per se insufficient for SBS suppression.

M.E. Likhachev, V.V. Alekseev, M.M. Bubnov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; e-mail: likhachev@fo.gpi.ru;
M.V. Yashkov, N.N. Vechkanov G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603950 Nizhnii Novgorod, Russia; N.I. Lobachevsky Nizhnii Novgorod State University, prosp. Gagarina 23, 603950 Nizhnii Novgorod, Russia;
A.N. Gur'yanov G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603950 Nizhnii Novgorod, Russia;
N. Peyghambarian, V. Temyanko, J. Nagel College of Optical Sciences, University of Arizona, 1630 East University Blvd., Tucson, AZ 85721, USA

Received 14 July 2014; revision received 12 September 2014
Kvantovaya Elektronika **44** (11) 1043 – 1047 (2014)
Translated by O.M. Tsarev

The purpose of this work is to identify the factors that determine conditions under which an antiguiding profile does lead to broadening of the SBS spectrum (and, as a consequence, to an increase in SBS threshold at a given mode field diameter). In particular, we report a study of three aluminosilicate fibres having an acoustically antiguiding configuration.

2. Experimental results

In the first stage of this study, two aluminosilicate fibres, Y-404 and Y-807, having cores almost uniformly doped with alumina, were fabricated by MCVD. The fibres differed only in the Al_2O_3 content and, hence, in the refractive index of their core (Fig. 1). The fibres had different diameters: the maximum diameter was determined by the condition of single-mode operation at a wavelength of 1550 nm, and the minimum diameter, by the condition that the leakage loss be reasonably low.

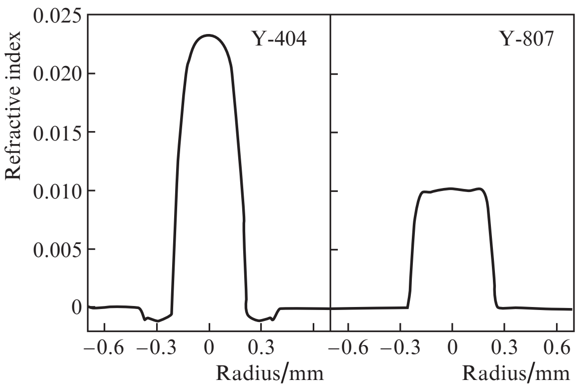

Figure 1. Measured refractive index profiles across the Y-404 and Y-807 fibre preforms.

SBS spectra of the Y-404 fibre were measured using Brillouin optical time-domain reflectometry (BOTDR) as described by Dragic [15]. For this purpose, we used an Ando AQ8602 Brillouin reflectometer. Figure 2 shows a schematic of the measurement system.

An input signal from a single-frequency light source (DFBLD) was split into a reference signal and main signal. The main signal was first modulated by an acousto-optic modulator (AO1) to produce pulses 20–1000 ns in duration (in order to ensure the required resolution along the length of the fibre). Next, a high-speed modulator (AO2) was used to form an optical signal with an increased optical frequency (the frequency shift, $+f$, is equal to the modulation frequency in AO2 and can be varied), which was in turn amplified by an erbium-doped fibre amplifier (EDFA). The amplified signal was directed to the input of an optical circulator and then launched into the test fibre. The backscattered light emerged from the third port of the circulator and was sent to a coherent detector circuit, where it was mixed with the reference signal and recorded using a photodetector. The time trace of the resultant signal enabled us to identify the region of the fibre where the light was scattered. Also, scanning the frequency of the AO2 modulator allowed the SBS spectrum to be measured. Note that the method used by us is incapable of determining the absolute SBS gain, so, for convenience, all the SBS spectra were normalised so that the peak SBS gain was unity. It should be emphasised that the relative intensity of the peak SBS gain can be estimated given that the area under the SBS spectra remains nearly unchanged (to within the variation in the fundamental mode field diameter). Thus, broadening of the SBS spectrum leads to a substantial decrease in peak SBS gain coefficient and, hence, to an increase in SBS threshold. It is the relative broadening of the SBS spectrum that was of interest in this study.

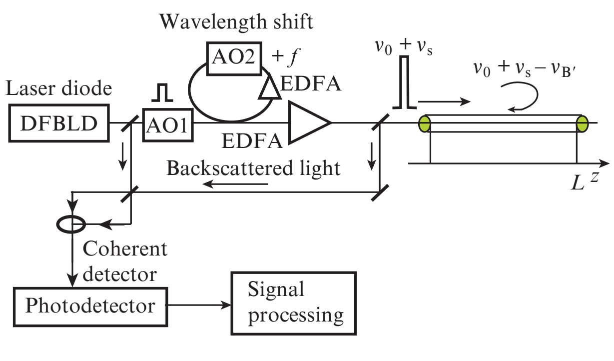

Figure 2. Schematic of the setup for measuring SBS spectra.

Figure 3 shows the measured SBS spectra of fibres drawn out from the Y-404 preform. The spectra are seen to have two peaks. The reason for this is that, despite the antiguiding acoustic refractive index profile, when light propagates through the fibre an acoustic wave is generated in the fibre core (where the optical field intensity is highest) and only then does it penetrate the cladding. Basically, several acoustic waves propagate through the fibre, each producing an SBS peak at its own frequency. The lowest frequency peak is due to the interaction of that part of the optical mode propagating in the cladding with the acoustic modes of the cladding, whereas the highest frequency peak is due to the overlap of the light propagating through the core with the acoustic modes of the core [16]. It should be specified here that, since the attenuation length of acoustic waves is of the same order as the cladding diameter and the guidance properties are extremely weak, the division of acoustic modes into cladding and core modes is in large measure arbitrary.

To ensure maximum SBS suppression (in comparison with a fibre having the same mode field diameter), the SBS gain spectrum should have two peaks of roughly equal height [15]. It can be seen from the spectra in Fig. 3 that the fibre of 100 μm outer diameter has the smallest difference in height between the peaks (Fig. 3a). It also can be seen that the relative height of the peaks in the SBS spectra depends on fibre diameter (Figs 3b, 3c). This effect can be accounted for by the fact that reducing the core diameter (proportional to the outer diameter of the fibre) increases the fraction of the electric field of the fundamental optical mode in the cladding. The result is an increase in the height of the lower frequency SBS gain peak (related to the acoustic modes of the cladding). At the same time, the decrease in the height of the higher frequency peak (arising from the acoustic mode of the core) with decreasing core diameter is caused by the decrease in the overlap of the acoustic modes of the core with the optical mode. Theoretical calculations of SBS spectra with allowance for the overlap between the optical and acoustic modes (using a model proposed by Koyamada et al. [17]) agree well with

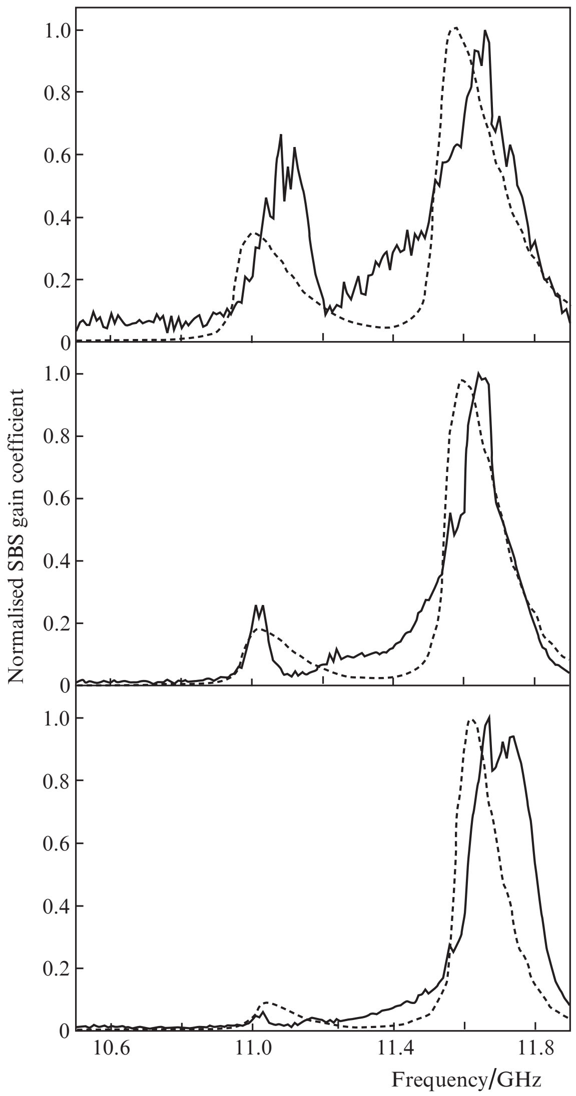

Figure 3. Measured (solid lines) and calculated (dashed lines) SBS spectra of fibres drawn out from the Y-404 preform and having outer diameters of (a) 100, (b) 125 and (c) 165 μm.

experimental data (Fig. 3) and lend support to this conclusion.

The procedure for measuring SBS spectra with the Ando AQ8602 is sufficiently simple and convenient. Its drawback is the relatively low signal-to-noise ratio, which makes it difficult to obtain quality SBS spectra. Because of this, in subsequent SBS spectrum measurements we used a direct method [18] and a setup schematised in Fig. 4. A signal from a single-frequency laser (DFBLD1) was amplified by an erbium-doped fibre amplifier (EDFA) and launched into a test fibre (F) through a circulator. A probe beam from a low-power tunable single-frequency laser diode (DFBLD2) was launched into the opposite end of the test fibre. Scanning the laser wavelength enabled the SBS gain spectrum to be measured with high accuracy. One advantage of this method over Brillouin optical time-domain reflectometry is that it offers a substantially higher signal-to-noise ratio.

The results for the Y-807 fibre demonstrate that, like above, its SBS spectrum has two distinct peaks (Fig. 5a). The relative height of the peaks depends on the size of the Y-807 fibre core. It is of interest to note that modelling the SBS spec-

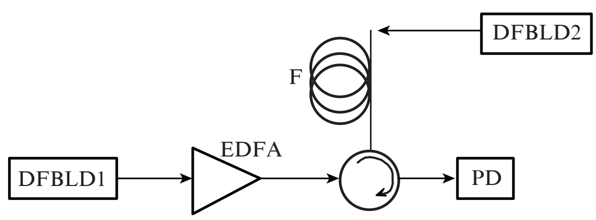

Figure 4. Schematic of the setup for measuring SBS spectra with the use of a probe beam.

trum shows in both cases that the relative heights of the lower frequency peak (due to SBS in the cladding) and higher frequency peak (arising from SBS in the core) depend on pump wavelength (Fig. 5b). The origin of this effect is completely similar to that of the influence of core diameter on the SBS spectrum (see above), because a change in pump wavelength is equivalent to a change in core diameter. In particular, increasing the operating wavelength increases the fraction of the optical mode propagating in the cladding, which is equivalent to a decrease in core size at a constant wavelength.

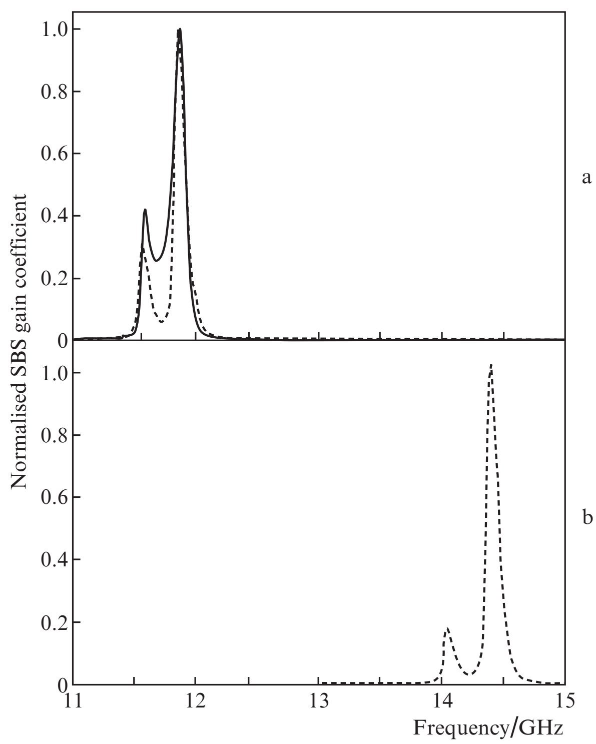

Figure 5. Measured (solid line) and calculated (dashed lines) SBS spectra of fibres drawn out from the Y-807 preform; wavelengths of (a) 1.55 and (b) 1.27 μm.

Note that we failed to equalise the heights of the peaks related to the acoustic modes of the cladding and core by varying the diameters of the Y-404 and Y-807 fibres. Modelling results indicate that the two peaks will be identical in height if the normalised frequency V will be reduced to 0.8 by reducing the fibre core diameter. However, the fibre will then be extremely sensitive to bending and will no longer transmit light. It should be emphasised that the refractive index of the core in both fibres (Y-807 and Y-404) considerably exceeds that in the standard telecom fibre SMF-28 (by a factor of 2 and 4, respectively), i.e. the fibre design under consideration generally has low bend sensitivity (compared to fibres with a nearly standard numerical aperture of the core). Thus, fibres with a steplike antiguiding structure (in which the acoustic index is constant throughout the cross section of the fibre core) are rather difficult to use in practice for SBS suppression. This is due to the rather unusual requirements for the guidance parameters of such fibres, which make it impossible to reach sufficiently low bend sensitivity. It seems likely that it is for this reason that Zou et al. [14] detected no broadening of the SBS spectrum of an acoustically antiguiding fluorosilicate fibre and no increase in SBS threshold.

In a number of studies, a triangular antiguiding acoustic index profile was proposed (in contrast to the nearly rectangular profile in the Y-807 and Y-404 fibres) for shifting the acoustic mode towards the cladding [19, 20]. Those studies considered codoping with germanium and aluminium oxides, whose concentrations were varied across the fibre core. The main idea of such doping is that germanium oxide increases both the optical and acoustic refractive indices of silica glass, whereas aluminium oxide increases only its optical refractive index, while decreasing its acoustic index. Doping the fibre core with an appropriate ratio of these oxides, one can obtain, in principle, almost any (different) acoustic and optical index profiles [19]. To verify the effectiveness of this approach, we fabricated a fibre, Y-814, containing two dopants: GeO_2 and Al_2O_3. Its refractive index profile (Fig. 6a) was essentially identical to that of Y-807 (Fig. 2b), which was singly doped with Al_2O_3. Figure 6b shows the measured dopant profiles across the Y-814 preform core.

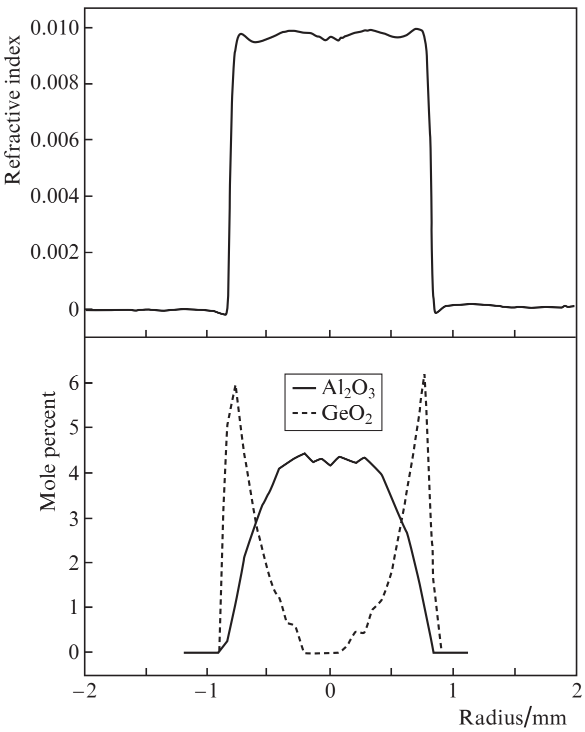

Figure 6. (a) Refractive index and (b) dopant profiles across the Y-814 fibre core.

The measured SBS spectrum of the Y-814 fibre showed that the problem in question had not been completely resolved: the spectrum was still dominated by one of the peaks (Fig. 7). At the same time, there was a significant distinction from the SBS spectra of the other two fibres: the lower frequency peak, corresponding to the overlap of the fundamental mode and the acoustic modes of the cladding, was stronger (in contrast to the case of uniform doping, where the higher frequency peak dominated). Thus, adjusting the GeO_2 and Al_2O_3 profiles across a fibre, one can, in principle, equalise the peak heights in its SBS spectrum (and, hence, minimise the peak SBS gain) at given guidance parameters of the fibre. In practice, a desired dopant profile is difficult to produce because of the rapid, uncontrolled thermal diffusion of aluminium in the preform/fibre fabrication process. In the case of success, it should be kept in mind that the fibre will have a maximum SBS threshold only at one wavelength (in contrast to, e.g., methods that use an alternating voltage or temperature or a dopant gradient along the length of the fibre), which considerably reduces the importance of this approach.

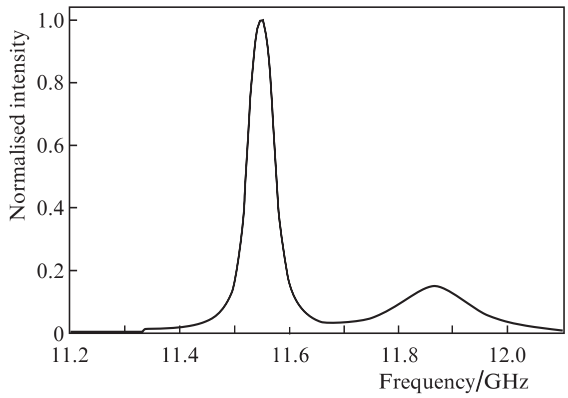

Figure 7. Measured SBS spectrum of the Y-814 fibre.

3. Conclusions

We have fabricated three acoustically antiguiding optical fibres and analysed their SBS spectra. The SBS spectrum has been shown to be influenced significantly by both the probe wavelength and fibre core size. In the case of a uniform dopant profile across the fibre core, the SBS spectrum can be broadened considerably by ensuring a sufficiently short cutoff wavelength (approximately one-third of the operating wavelength), which would, however, result in too high a bend sensitivity of the fibre. This problem can be resolved by carefully adjusting the profiles of dopants that ensure opposite signs of the acoustic refractive index.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 13-02-01267) and in part by the RF Ministry of Education and Science (Agreement No. 02.V.49.21.0003 between the RF Ministry of Education and Science and Nizhni Novgorod State University, 27 August 2013).

We are grateful to S.G. Akopov (OOO Corning SNG) for his technical assistance with this study and E.M. Dianov for his support of and continuous interest in this work.

References

1. Smith R.G. *Appl. Opt.*, **11**, 2489 (1972).
2. Agrawal G.P. *Nonlinear Fiber Optics* (New York: Academic Press, 1995).
3. Takahashi M., Tadakuma M., Hiroishi J., Yagi T. *Proc. ECOC 2007* (Berlin, 2007) paper P014.
4. Tateda M., Ohashi M., Shiraki K. *Proc. OFC 1993* (San Jose, 1993) paper ThJ4.
5. Achmetshin U.G., Bubnov M.M., Guryanov A.N., Dianov E.M., Khopin V.F., Sysoliatin A.A., Li M.-J., Li S., Nolan D.A. *Proc. ECOC 2005* (Los Angeles, 2005) paper OFH5.
6. Liu A. *Opt. Express*, **15**, 977 (2007).
7. Rothenberg J.E., Thielen P.A., Wickham M., Asman C.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **6873**, 68730O (2008).
8. Zel'dovich B.Ya., Pilipetskii A.N. *Kvantovaya Elektron.*, **15** (6), 1297 (1988) [*Sov. J. Quantum Electron.*, **18** (6), 818 (1988)].
9. Dianov E.M., Karasik A.Ya., Luchnikov A.V., Pilipetskii A.N. *Kvantovaya Elektron.*, **16** (4), 752 (1989) [*Sov. J. Quantum Electron.*, **19** (4), 491(1989)].
10. Thomas P.J., Rowell N.L., van Driel H.M., Stegeman G.I. *Phys. Rev. B*, **19**, 4986 (1979).
11. Jen C.-K., Neron C., Shang A., Abe K., Bonnel L., Kushibiki J. *J. Am. Ceram. Soc.*, **76**, 712 (1993).
12. Nakanishi T., Tanaka M., Hesegawa T., Hirano M., Okuno T., Onishi M. *Proc. ECOC 2006* (Cannes, 2006) Vol. 6 , paper Th4.2.2.
13. Mermelstein M.D. *Opt. Express*, **17**, 16225 (2009).
14. Zou W., He Z., Hotate K. *Proc. OFC 2008* (San Diego, 2008) paper OMH1.
15. Dragic P.D. *Proc. SPIE Int. Soc. Opt. Eng.*, **7197**, 719710-2 (2009).
16. Yoo S., Codemard C.A., Jeong Y., Sahu J.K., Nilsson J. *Appl. Opt.*, **49**, 1388 (2010).
17. Koyamada Y., Sato S., Nakamura S., Sotobayashi H., Chujo W. *J. Lightwave Technol.*, **22**, 631 (2004).
18. Villafranca A., Lázaro J.A., Salinas I., Garcés I. *Opt. Express*, **13**, 7336 (2005).
19. Mermelstein M.D., Andrejco M.J., Fini J., Yablon A., Headley C., DiGiovanni D.J., McCurdy A.H. *Proc. SPIE Int. Soc. Opt. Eng.*, **6873**, 68730N (2008).
20. Nanii O.E., Pavlova E.G. *Kvantovaya Elektron.*, **39** (8), 757 (2009) [*Quantum Electron.*, **39** (8), 757 (2009)].