Laser Physics, Vol. 14, No. 9, 2004, pp. 1227–1230.

Multiple Output Wavelength Composite Raman Fiber Converter

N. Kurukitkoson[1], S. K. Turitsyn[1], A. S. Kurkov[2], and E. M. Dianov[2]

[1] *Photonics Research Group, Department of Electronic Engineering & Applied Physics, Aston University,*
Birmingham, B4 7ET, UK
e-mail: kurukitn@aston.ac.uk
[2] *Fiber Optics Research Center, General Physics Institute, e Russian Academy of Sciences,*
ul. Vavilova, 38, Moscow, 117756 Russia

Received November 21, 2003

Abstract—This paper presents a novel design and performance analysis of a multiple output wavelength composite Raman fiber converter. The converter comprises two sections: (1) phosphosilicate and (2) germanium (Ge) doped fiber sections. The characteristics and performance of the converter are analyzed by using numerical modeling techniques. The optimization of key parameters is performed to ensure the highest conversion performance. An overall conversion efficiency of 28% is achieved. The characteristics of the optimal regime are also analyzed. The optimal regime is rather tolerant to the deviation of key parameters from their optimal values.

INTRODUCTION

Multi-wavelength-pump silica-fiber Raman amplifiers have become a key technology to widen the overall gain bandwidth while simultaneously reducing its spectral nonuniformity in telecom applications. One of the major advantages comes from the fact that it can accommodate signals over a large bandwidth providing simultaneous amplification to a large number of channels in wavelength division multiplexing systems.

Broadband Raman amplifiers exploiting 12 pump sources have been reported to achieve a gain flatness as good as 0.1 dB over C+L bands (1527–1607 nm) [1]. In order to design a broadband Raman amplifier, however, one must consider the tradeoff between its advanced characteristics and its overall costs. In many applications, it is reasonable to choose moderate gain flatness over a wide spectral range using, instead, a minimal number of pump sources. Such a device, obviously, would be easier to maintain and be a cost-effective solution compared to the many-pump configuration. In [2], a simple direct approach to designing a flat gain Raman amplifier with a bandwidth ranging from 1520–1595 nm and suppressed gain ripples has been reported. The optimal amplifier configuration requires only three pumps to achieve a gain ripple of less than 1.7 dB.

In addition to the simplicity and flexibility in operation of the broadband Raman amplifiers, a compact and efficient pump source is required. Due to its simple structure and potentially low cost, a Raman fiber converter (RFC) pumped by a semiconductor laser is an interesting candidate [3, 4]. The converter transfers the pump power into a number of Stokes lines resonated in nested cavities through a stimulated Raman scattering process [5].

In this paper, we present a novel design and performance analysis of a multiple output wavelength composite Raman fiber converter aimed for use as a pump source for the above amplifier.

LASER DESIGN

Figure 1 illustrates a schematic diagram of the laser setup. The converter comprises two sections. The first section converts the wavelength from 1080 nm (λ_P) to 1263 nm (λ_1). The chosen gain medium is phosphosilicate core fiber to minimize the number of stages required, which thus may result in a lower cost and less expensive optical scheme [6]. Note that the choice of the pump wavelength of 1080 nm is due to the highest slope efficiency of the double-clad Yb-doped fiber laser used as a pump source for the composite RFC [7]. The second section is a multiple output wavelength Raman fiber converter based on Ge-doped fiber to provide efficient wavelength conversions from 1263 nm to 1420 nm (λ_3), 1437.2 nm (λ_4), and 1480 nm (λ_5). The nested cavities are formed by pairs of FBGs with high

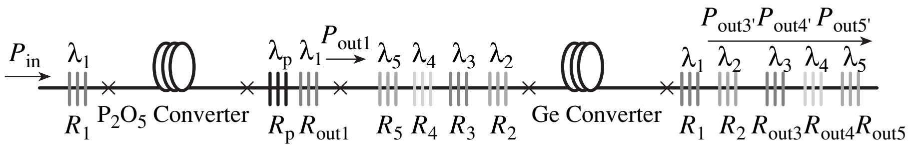

Fig. 1. Multiple output wavelength composite Raman fiber converter schematic.

Optimal configuration of the P-doped section for a given input power

P_{in} (W)	R_{out1} (%)	L_1 (m)	Conv. eff. (%)
2	31.8	490	57.8
3	22.5	437	63.9
4	16.8	399	67.5
5	13.0	373	69.9

reflectivities, except for each output grating, which has a moderate reflectivity to couple the light out of the cavity. In numerical modeling works, we have analyzed and performed parameter optimizations for each section separately.

CAVITY MODELING AND OPTIMIZATION

In our simulations, we modified a well-known model described in [8] to account for all possible power transfers among the Stokes waves in the cavities. The set of differential equations are solved numerically for both forward and backward propagating waves using two point boundary conditions given by the injected input power and reflections at the Bragg gratings. The model includes realistic parameters for both distributed and lumped (splicing) losses. For the first section (P-doped fiber), we used the optimization scheme detailed in [6] to determine the optimal cavity length and output coupler for a considered input power. The optimization results for some chosen input powers, as well as the expected conversion efficiency, are given in the table. We achieved a fairly high conversion efficiency of 67.5% for $P_{\text{in}} = 4$ W due to the smaller cavity loss, as only one stage is required for the phosphosilicate gain medium. For the multiple output wavelength section, the power partitioning can be controlled by adjusting the output grating reflectivities (R_{out3}, R_{out4}, R_{out5}) and the power launched into the section (P_{out1}). Note that the adjustment is not straightforward due to the nonlinear nature of the process. An appropriate combination of output reflectivities and power yielding a desired power partition can be found by applying a simple downhill simplex algorithm.

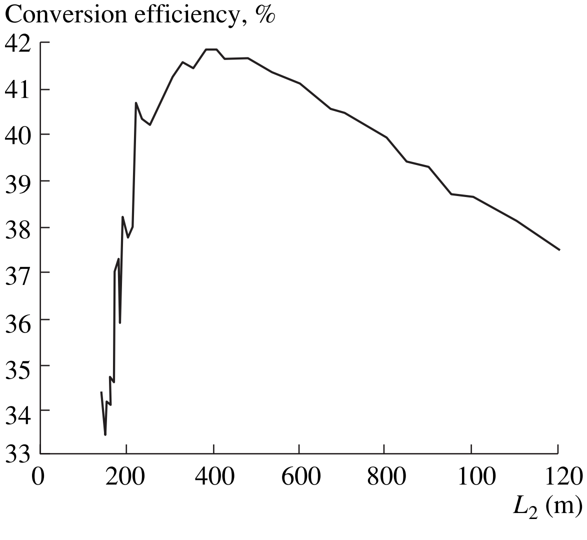

Fig. 2. Conversion efficiency of the multiple output wavelength section as a function of its cavity length.

To achieve the highest performance of the converter, we performed a search for an optimal cavity length giving the highest conversion efficiency. The cavity is optimized for the power partition of 339, 333, and 328 mW at 1420, 1437.2, and 1480 nm, respectively, which is the optimal power partition required for a flat gain three-wavelength pumped Raman amplifier with a 70-nm bandwidth discussed in [2]. Figure 2 shows a variation of the conversion efficiency with the cavity length. The degradation of the conversion efficiency when the cavity is too short is due to the fact that there is not enough cavity length to allow an efficient power transfer among the Stokes waves. For a too long cavity, the cavity loss will play a critical role to degrade the conversion performance. The highest conversion efficiency of 41.9% is found at $L_2 = 380$ m, and the appropriate combination of R_{out3}, R_{out4}, and R_{out5} is 51%, 35%, and 28%, respectively. This leads to a total conversion efficiency of the composite converter of approximately 28%. One may also find in Fig. 2 how the converter performance is tolerant to a deviation of the cavity length. The conversion efficiency is degraded by less than 1.5% when the cavity length deviates from its optimal value for ±100 m, which evidently shows the high tolerance of the optimal regime. One may see that overestimating cavity length does less harm to the converter performance and the conversion efficiency, which in this case degrade only a little beyond the optimal values.

CHARACTERISTICS OF THE OPTIMAL REGIME

In the practical use of the converter, the partition setting may be required to change. One may be interested to know how the conversion efficiency varies with the partition setting. We investigated the variation of the conversion efficiency at various power partition settings. Figure 3a illustrates the variation of the conversion efficiency when fixing P_{out5} to the optimal setting and varying P_{out3} and P_{out5}. Note that the total output power ($P_{\text{out3}} + P_{\text{out4}} + P_{\text{out5}}$) is maintained constant at 1 W in all cases. The conversion efficiency varies almost monotonically with the adjustment of P_{out3} and is in the range of 38–48%. Similarly, Fig. 3b depicts the variation of the conversion efficiency when fixing P_{out5} and varying the rest but still maintaining the total output power of 1 W. The conversion efficiency still varies in the range of 35–47%. Last, we fixed P_{out3} and varied the rest. The result is shown in Fig. 3c. In this case, the con-

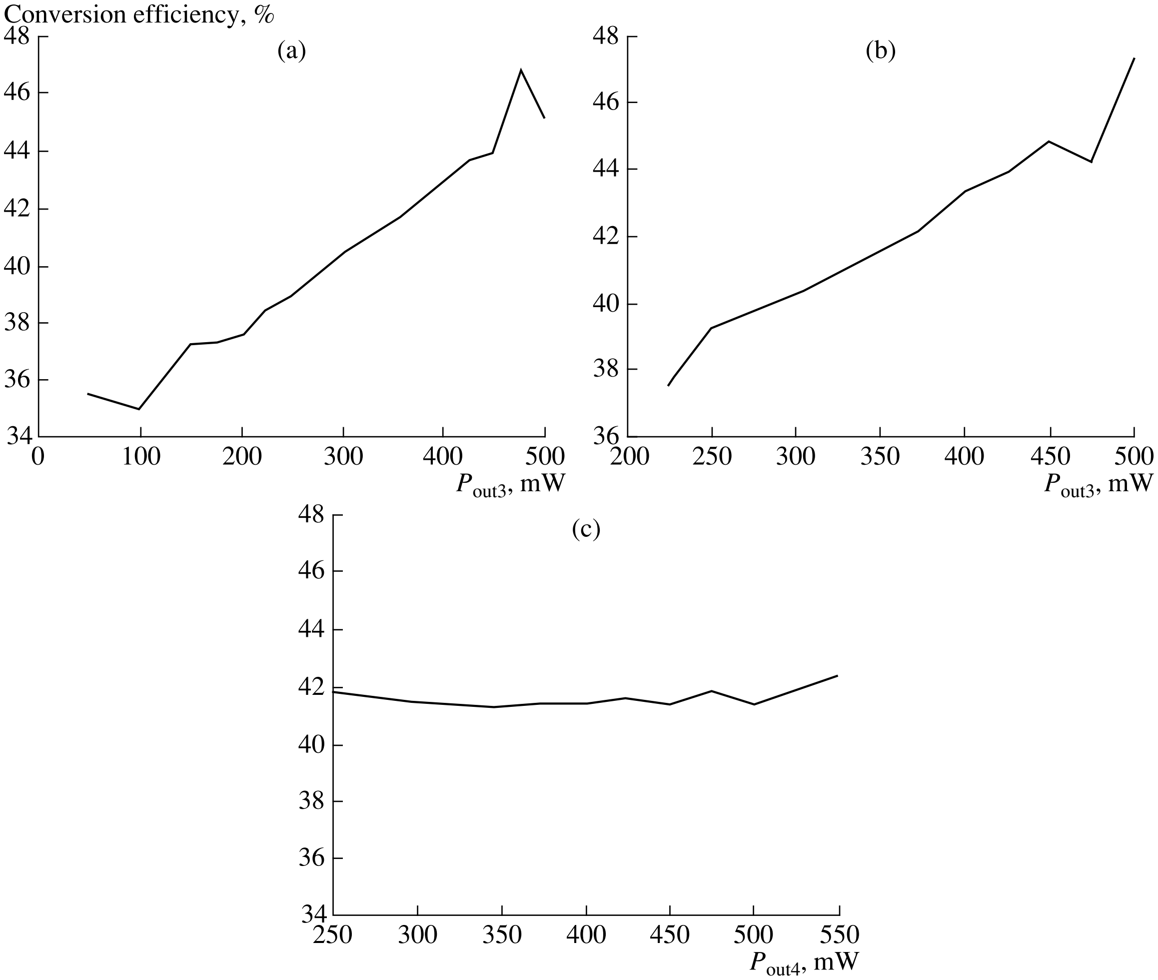

Fig. 3. Variation of conversion efficiency against the deviation of output powers from their optimal setting.

version efficiency is nearly constant and takes a value of approximately 42%. This observation can be described easily be considering the fact that the longer wavelength outputs rely partly on the power transfer from P_{out3} and thus is sensitive to the variation of P_{out3}. Nevertheless, Fig. 4c still confirms the high tolerance of the optimal regime if P_{out3} is fixed. This fact is beneficial from the engineering point of view, where freedom and convenience in designing the converter are of importance.

To emphasize the tolerance of the optimal regime, we performed a number of cavity optimizations for various power partition settings. By fixing P_{out3} and the total output power, we define ΔP as a power adjustment variable, such that

$$P'_{out3} = P_{out3,\,opt}, \quad P'_{out4} = P_{out4,\,opt} + \Delta P, \quad P'_{out5} = P_{out5,\,opt} - \Delta P, \tag{1}$$

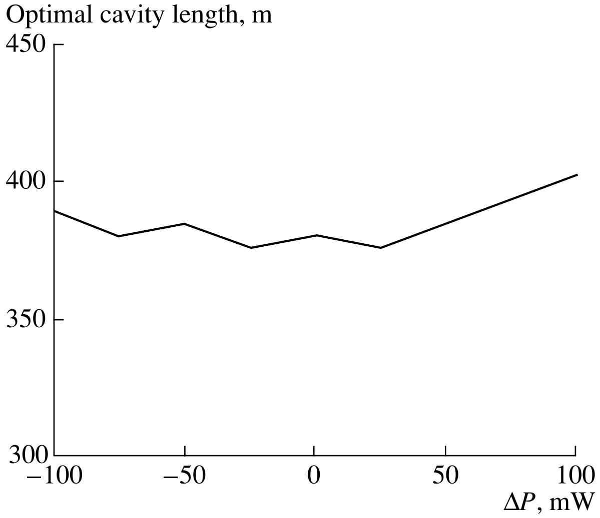

Fig. 4. Optimal cavity length at various power partition setting.

where $P_{\text{out3, opt}}$, $P_{\text{out4, opt}}$, and $P_{\text{out5, opt}}$ are the power partition setting used in the optimization earlier. Figure 5 shows the plot of optimal cavity length against ΔP. The results show that the optimal cavity length varies in the range of only 25 m. Considering this fact, an optimal design for a typical power partition setting should warrant a good performance at other partition settings as well.

CONCLUSIONS

In this paper, we propose a novel design of a multiple output wavelength composite Raman fiber converter. The converter performance and

characteristics have been analyzed by using numerical modeling techniques. Optimization of the converter parameters to achieve the highest performance has been carried out. A fairly high conversion efficiency of 67.5% has been achieved for the phosphosilicate section. The germanium section reveals a maximum efficiency of 42%, leading to a total conversion efficiency of 28% for the device. We also investigated the characteristics of the optimal regime. The converter conversion efficiency is more sensitive to the power adjustment of the shortest output wavelength due to a cascading effect. However, the optimal regime is rather tolerant to a deviation of the parameters from the optimal values.

REFERENCES

1. S. Namiki and Y. Emori, IEEE J. Sel. Top. Quantum Electron. **7**, 3 (2001).
2. J. D. Ania-Castanon, S. M. Kobtsev, A. A. Pustovskikh, and S. K. Turitsyn, in *Proceedings of 15th Annual Meeting of the IEEE LEOS* (2002), Paper WQ4, p. 500.
3. M. D. Mermelstein, C. Horn, Z. Huang, *et al.*, in *Proceedings of OSA Optical Fiber Conference* (2002), Paper TuJ2, p. 59.
4. X. Normandin, F. Leplingard, E. Bourova, *et al.*, in *Proceedings of OSA Optical Fiber Conference* (2002), Paper TuB2, p. 9.
5. G. Agrawal, *Nonlinear Fiber Optics,* 3rd ed. (Academic, San Diego, 2000; Mir, Moscow, 1996).
6. N. Kurukitkoson, H. Sugahara, S. K. Turitsyn, *et al.*, Electron. Lett. **37**, 1281 (2001).
7. N. Kurukitkoson, S. K. Turitsyn, O. N. Egorova, *et al.*, in *Proceedings of OSA Tropical Meeting on the Optical Amplifiers and Their Applications* (2004), Paper OMC4.
8. M. Rini, I. Cristiani, and V. Degiorgio, IEEE J. Quantum Electron. **36**, 1117 (2000).