Optimisation of two-stage Raman converter based on phosphosilicate core fibre: modelling and experiment

N. Kurukitkoson, H. Sugahara, S.K. Turitsyn, O.N. Egorova, A.S. Kurkov, V.M. Paramonov and E.M. Dianov

Parameter optimisation of a two-stage Raman converter based on phosphosilicate-core fibre is presented. The optimal operational regime is determined and its tolerance against variations of laser parameters is examined. Results of numerical modelling are in a good agreement with experimental data.

Introduction: Multi-wavelength pumping is a key technique to expand a gain bandwidth of distributed Raman amplification that rapidly becomes an attractive technology in large-capacity transmission [1, 2]. Considerable attention has recently focused on the development of Raman fibre converters (RFCs), which can be used as a pump source for Raman and erbium-doped fibre amplifiers. The lasers convert the pump power to the highest-order Stokes line resonating in nested cavities. RFCs typically employ GeO_2 doped fibres as the active medium which posseses a rather small Stokes shift (440 cm^{-1}). Consequently, a large number of cascades in Raman frequency conversion to the long-wavelength are required, leading to a complicated and expensive optical scheme and decreased efficiency. A means of avoiding this complication is the use of P_2O_5 doped silica fibres, where, owing to the large Raman shift (1330 cm^{-1}) in the phosphosilicate fibre, the number of required cascades can be significantly reduced [3, 4]. The performance of the RFC depends on few system parameters such as characteristics of the output coupler, cavity length, etc. Therefore, before fabrication of the device some optimisation is required to build optimal performance of the RFC.

This Letter describes how, by applying numerical modelling, we have optimised parameters of a two-stage RFC based on phosphosilicate fibre and investigated the tolerance of a found optimal regime against variations of the laser characteristics. Using results of the modelling and optimisation, an RFC with advanced performance has been fabricated. Good agreement between theoretical predictions and the results of experiment is demonstrated.

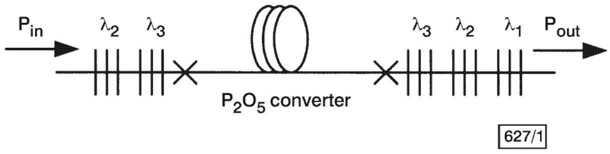

Fig. 1 *Schematic diagram of laser*

Table 1: P_2O_5 fibre parameter

Wavelength	α	G_R/A_{eff}
nm	dB/km	Wm^{-1}
$\lambda_1 = 1061$	1.55	1.29×10^{-3}
$\lambda_2 = 1240$	0.92	0.94×10^{-3}
$\lambda_3 = 1480$	0.75	—

Laser characteristics and cavity optimisation: In our simulations, we employed the model described in [5] that accounts for all interactions between forward and backward travelling waves. We numerically solved the well-known (see [5] for more detail) differential equations for both forward and backward propagating waves using two-point boundary conditions given by the reflections at the Bragg gratings. The model included realistic parameters for both distributed and lumped (splicing) losses. The schematic diagram of the laser setup is shown in Fig. 1. First, the Yb-laser pumped by semiconductor source at 978 nm generates input to the RFC at 1061 nm. Since the Raman shift in phosphosilicate is around 1330 cm^{-1}, conversions from 1061 to 1480 nm occur through cascaded Raman scattering involving intermediate wavelength of 1240 nm. The converter presents the phosphosilicate-core singlemode fibre with 13 mol.% P_2O_5 doping level [6]. This corresponds to the Raman gain coefficients and fibre losses as summarised in Table 1. Bragg reflectors with 99% reflectivities, except for the output reflector, are considered. The sum of one-path splicing loss and background loss of Bragg gratings in this scheme was equal to $2 \times 4\% = 8\%$ (0.36 dB).

To optimise the laser parameters we evaluated the performance of the RFC considering as a figure of merit the conversion efficiency η defined as $\eta = P_{out}/P_{in}$. The performances of RFCs are dependent on several parameters: reflectivity of the output coupler R_{out}, cavity length L and input power P_{in}. First, we performed numerical optimisation of the laser performance, varying these three main parameters.

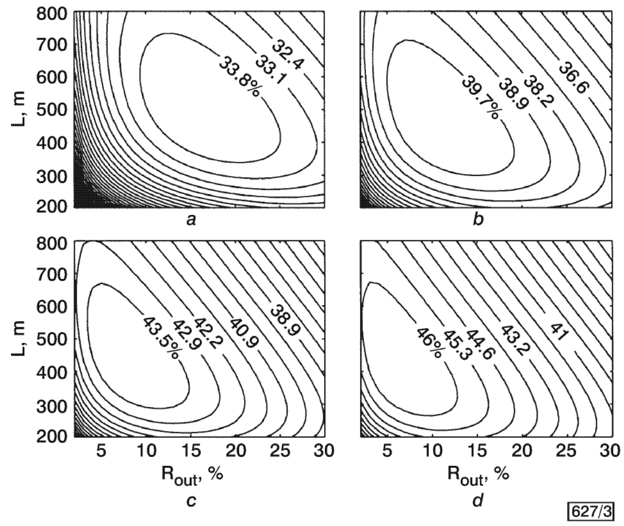

Fig. 2 *Contour plots of conversion efficiency at various P_{in}*

a P_{in} = 2 W
b P_{in} = 3 W
c P_{in} = 4 W
d P_{in} = 5 W

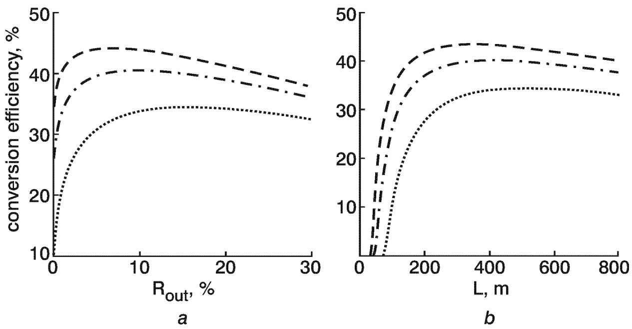

Fig. 3 *Tolerance of RFC performance to deviations in reflectivity of output coupler and cavity length*

a Reflectivity (L = 500 m)
b Cavity length (R_{out} = 15%)
············· 2 W
–·–·–·– 3 W
– – – – 4 W

Fig. 2 shows the contour plots of η over the variations in R_{out} and L for several P_{in}. According to the plots, the optimal regimes are found for each P_{in} yielding the highest performance, e.g. for an RFC operating at P_{in} = 2 W the optimal cavity length and the optimal reflectivity of the output coupler are 500 m and 16%, respectively. The conversion efficiency of 34% is achieved in this case. The conversion efficiency, however, increases as the input power is increased since the higher input power will enhance the conversion rate from the lower Stoke wave into the higher one. It is interesting to note that both optimal cavity length and optimal output coupler reflectivity move towards the lower values as the input power increases. This can be explained as follows. First, as discussed, the higher input power enhances the conversion rate. The cavity for a laser operating at a high power input need not to be long, otherwise it will suffer from fibre attenuation. Similarly the output coupler reflects back some energy. This backward light again helps enhance the conversion rate, which is especially important for the low input power. However, too strong an output coupler limits the laser performance and should be weaker for the higher input power. Therefore, there is a different optimal regime for each input power. Fortunately, due to high tolerance of the optimal regime against deviations of the key parameters (as discussed in detail in the following Section), the RFC parameters optimised at a chosen P_{in} are good enough for the practical design without losing too much performance. Note that it was convenient to choose 15% reflectivity for the experiment.

Tolerance of optimal regime: We now investigate the tolerance of laser performance to the deviations in a reflectivity of the output coupler and cavity length. Figs. 3*a* and *b* show the conversion efficiencies of the RFC under deviations from the optimum of R_{out} (L = 500 m) and L (R_{out} = 15%), respectively. It can be seen that the laser performance degrades by less than 1% for ±5% R_{out} deviation from the optimal value as does the performance for L deviation of ±100 m from the optimal value. It can also be seen that overestimate of these two parameters does less harm to the laser performance and the conversion efficiency which in this case degrade only a little bit beyond the optimal values.

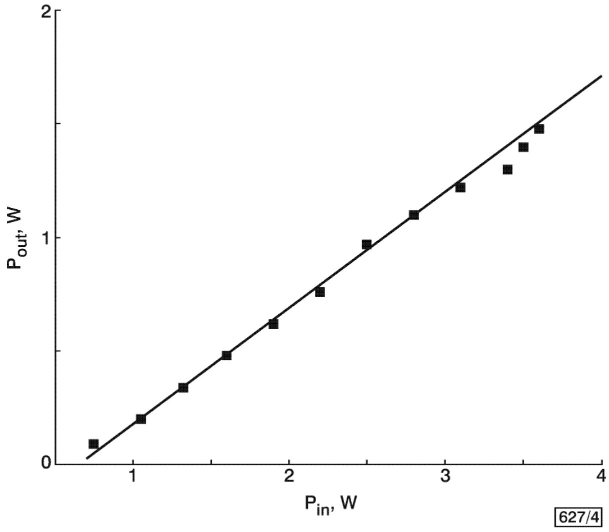

Fig. 4 *Comparison of experimental results and simulations*

R_{out} = 15%, L = 500 m
■ experiment
——— simulation

Comparison with experimental results: Using results of the optimisation we have realised a two-stage converter based on the P-doped fibre specified in Table 1. The fibre length was 500 m. The converter was pumped by Yb-doped double-clad fibre laser having a maximum output power of 3.8 W at 1061 nm. This power was achieved for a semiconductor source power at 978 nm equal to 5.8 W. The dependence of the output power at 1480 nm against the input power of the pumping Yb laser, and results of the simulation, are shown in Fig. 4.

Using the results of the modelling and optimisation, a phosphosilicate-core RFC with enhanced performance has been fabricated. Good agreement between theoretical predictions and the results of experiment has been demonstrated.

27 July 2001
Electronics Letters Online No: 20010848
DOI: 10.1049/el:20010848

N. Kurukitkoson, H. Sugahara and S.K. Turitsyn (*Photonics Research Group, Department of Electronic Engineering and Applied Physics, Aston University, Birmingham, B4 7ET, United Kingdom*)

E-mail: kurukitn@aston.ac.uk

O.N. Egorova, A.S. Kurkov, V.M. Paramonov and E.M.Dianov (*Fiber Optics Research Center, General Physics Institute of the Russian Academy of Sciences, 117756, Vavilov Str. 38, Moscow, Russia*)

References

1 DIANOV, E.M.: ‘Advances in Raman amplifier fibres’. OFC’2001, 2001, Paper MA1-1
2 CHERNIKOV, S.V., LEWIS, A.E., and TAYLOR, J.R.: ‘Boradband Raman amplifiers in the spectral range of 1480-1620 nm’. OFC’ 1999, 1999, Paper WG6-1
3 PRABHU, M., KIM, N.S., JIANREN, L., and UEDA, K.: ‘Output characteristics of high-power continuous wave Raman fiber laser at 1484 nm using phosphosilicate fiber’, *Opt. Rev.,* 2000, **7**, (5), pp. 455–461
4 DIANOV, E.M., GREKOV, M.V., BUFETOV, I.A., VASILIEV, S.A., MEDVEDKOV, O.I., PLOTNICHENKO, V.G., KOLTASHEV, V.V., BELOV, A.V., BUBNOV, M.M., SEMJONOV, S.L., and PROKHOROV, A.M.: ‘CW high power 1.24 and 1.48 µm Raman lasers based on low loss phosphosilicate fibre’, *Electron. Lett.,* 1997, **33**, (18), pp. 1542–1544
5 RINI, M., CRISTIANI, I., and DEGIORGIO, V.: ‘Numerical modeling and optimization of cascaded CW Raman fiber lasers’, *IEEE J. Quantum Electron.,* 2000, **36**, (10), pp. 1117–1122
6 EGOROVA, O.N., BUBNOV, M.M., BUFETOV, I.A., DIANOV, E.M., GURYANOV, A.N., KHOPIN, V.F., SEMJONOV, S.L., and SHUBIN, A.V.: ‘Phosphosilicate-core single-mode fibers intended for use as active medium of Raman lasers and amplifiers’, *Proc. SPIE,* 2001, **4216**, pp. 32–39