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Spontaneous pump depolarization in ultralong cavity Raman fiber laser amplifiers

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Abstract: We present an experimental demonstration of polarization-independent performance in a forward and backward-pumped 2nd-order ultralong cavity Raman laser amplifiers with highly polarized pumps. Our findings show that the depolarization of the Stokes component due to gain saturation leads to polarization-insensitive performance in terms of output gain and relative intensity noise in the signal. These results pave the way for the use of individual highly polarized low-RIN semiconductor laser diodes in Raman-amplified optical communications.

1. Introduction

Polarization dependent gain (PDG) [1,2] in Raman amplifiers is a potential source of amplitude noise in optical fiber communications that is generally considered to impose the need for depolarized pump lasers. Under this paradigm, system designers typically rely on two different kinds of pump lasers depending on the specific on-off gain requirements of the system: intense pumping such as the one required for distributed amplification [3] is provided by inherently noisy but depolarized fiber lasers, whereas lower-powered orthogonally polarized pairs of low-noise semiconductor lasers can be combined to produce circularly polarized pumps for discrete amplification purposes [4,5]. Thus, system designers face a less-than-ideal scenario when dealing with Raman-amplified systems requiring moderate to high gains. The use of higher power fiber laser pumps implies signal degradation due to relative intensity noise (RIN) transfer from high-RIN fiber laser pumps [6,7], but pumping with low-noise semiconductor laser pumps while avoiding RIN generation due to PDG [2] requires the use of polarization beam combiners [8,9] doubling the number of lasers and reducing pumping efficiency due to combiner losses.

The RIN transfer function cut-off frequency strongly depends on the selected pumping scheme [6], and specifically, the transfer of high-frequency RIN components can be reduced by using backward (BW) pumping, due to the shorter interaction length between pump and signal. For this reason, counter-propagating pumping is more commonly used in practice, thus frustrating the benefit associated with improved amplified spontaneous emission (ASE) noise performance thanks to the presence of forward (FW) pumping [10,11]. A potential optimal performance balance can be found, in some situations, by combining both kinds of pumping schemes, with semiconductor lasers providing pumping in the FW direction.

Other solutions have been recently investigated to mitigate RIN-related impairments connected to the use of fiber laser sources in FW configuration. For instance, random distributed feedback laser amplifiers [12,13] and the use of broadband pumps [14] have proven useful for extending the communication distance in long-haul transmission systems. Nevertheless, such interesting results have been achieved at the expense of a strong degradation of efficiency and higher architecture complexity, which translates into increased cost.

Here, we demonstrate for the first time that secondary pump depolarization due to gain saturation [15,16] is an inherent characteristic of second-order ultralong cavity Raman fiber

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laser (URFL) amplifiers [17], which allows the use of highly polarized primary pumps with no negative impact on the PDG, gain efficiency or RIN transfer. We study both FW and BW pumping configurations, demonstrating that the use of the URFL architecture effectively removes the need for orthogonally polarized sources and polarization beam combiners to achieve circular polarization.

2. Experimental setup

The system is set up according to the typical scheme of a cavity URFL shown in Fig. 1. The fully closed cavity is composed of a high-reflectivity fiber Bragg grating (FBG) with 0.5 nm bandwidth centered at 1455 nm at both sides of an optical fiber. 50 km of standard single mode fiber (SMF) or 2 km of dispersion compensating fiber (DCF) are alternatively used as the gain medium inside the cavity for comparison, but also to investigate the potential use of this configuration in discrete Raman amplification. Two 3x1 wavelength division multiplexers (WDMs) are used to couple the 1366 nm primary pump and the 1550 nm continuous wave signal into the cavity, as well as to monitor the 1455 nm Stokes component generated inside the cavity by the primary pump. The main fiber parameters are presented in Table 1.

Table 1. Main fiber parameters.

	Length	Loss @ 1366 nm	Loss @ 1455 nm	Loss @ 1550 nm	PMD	Raman Gain @ 1455 nm	Dispersion @ 1550 nm
SMF	50	0.32	0.28	0.19	0.045	0.5	18
DCF	2	1.02	0.66	0.48	< 0.04	1.94	−172
Unit	km	dB/km	dB/km	dB/km	$ps/km^{1/2}$	1/(W·km)	ps/(nm·km)

The primary pump is a high power depolarized fiber laser with 8 W maximum output power and −120 dBc/Hz nominal RIN level. As the pump RIN changes with the laser current [18], the pump output is connected to a variable optical attenuator (VOA) that allows to vary the pump power while keeping a constant output RIN. The depolarized pump is then linearly re-polarized through a calcite crystal polarizer and sent either to the input or the output WDM, to act as FW or BW pump respectively. Pump degree of polarization (DOP) is in excess of 98% and any state of polarization (SOP) can be achieved by way of polarization controllers (PCs) on both the signal and the pump optical paths. Pump attenuation is of the order of 6 dB when the polarizing stage is included, which limits the maximum achievable pump power at the cavity input to about 32 dBm.

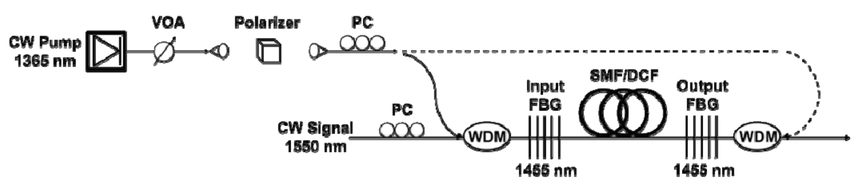

Fig. 1. Schematic diagram of the second-order URFL with polarized pump.

After band-pass optical filtering, the polarization properties of the output amplified signal and the generated 1455 nm secondary pump are observed through a Thorlabs PAX1000IR2 polarimeter, and the output signal RIN measured through a low noise photodetector with 125 MHz bandwidth and an electrical spectrum analyzer. The collected RIN traces are then integrated over the [9 kHz, 1 MHz] RF frequency bandwidth to extrapolate the overall signal RIN level. Each measurement was performed individually and independently from the others.

3. Secondary pump depolarization

Closed-cavity ultralong Raman fiber laser amplifiers operate in saturation, with the bidirectionally propagating Stokes components (secondary pumps) lasing at their steady-state

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power level and providing distributed gain to a signal in the C transmission window [2,17]. From Raman polarization attraction theory [15] and experimental observation in first-order Raman polarizers [16], it is possible to infer that operation in the gain saturation regime with high enough gain could offer some degree of depolarization of the Stokes components in ultralong cavity configurations.

In order to confirm this prediction, we measured the evolution of the 1455 secondary pump inside the cavity for different values of the primary pump power. Results are summarized in Fig. 2(a), where a strong reduction of the secondary pump DOP is observed as primary pump power is increased, eventually leading to complete depolarization in the case of a DCF cavity and strong depolarization in the case of an SMF cavity. Full depolarization cannot be observed in the case of the SMF cavity, as available pump power limits maximum Stokes gain.

Please note that the presence of a plateau in the depolarization figure reflects the presence of an equivalent plateau in the evolution of the gain caused by the broadening of the secondary pump and the increase of losses at the grating reflector [19]. This broadening takes place at higher pump powers in the case of the SMF, due to the higher nonlinear coefficient of DCF.

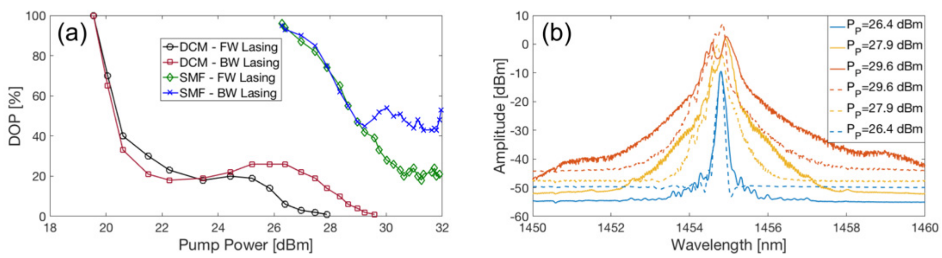

Fig. 2. (a) Secondary pump DOP vs. primary pump power for 50 km DCF (black - FW lasing, red - BW lasing) and SMF (green - FW lasing, blue - BW lasing) URFL cavities. (b) Secondary pump power spectra for different primary pump powers (solid - FW lasing, dashed - BW lasing).

4. Impact on signal amplification

A complete experimental study of the performance of forward and backward pumped configurations has been carried out for both a 50 km SMF span cell and a 2 km dispersion compensating fiber module (for discrete Raman amplification), comparing the gain and the RIN integrated over 1 MHz obtained with both polarized and depolarized pumps at the achievable pump power levels. In the case of the polarized pump, polarization control was adjusted in order to find the worst performance.

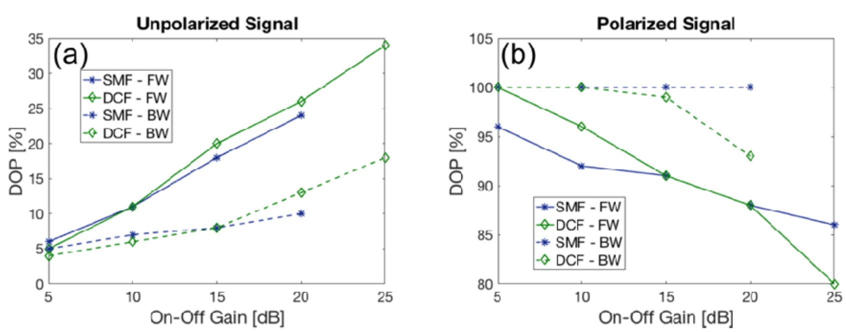

Fig. 3. Output signal DOP vs. signal On-Off gain, for a depolarized (a) and polarized (b) signal, using forward (solid) and backward (dashed) fully polarized 2nd order pumping in SMF (blue, stars) and DCF (green, diamonds) fiber cavities.

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Contrary to expectations based on the behavior of 1st-order amplification schemes, the 2^{nd} order amplification scheme based on URFL is extremely robust with respect to the degree and state of polarization of the pump, both in the forward and backward pumping cases. Indeed, no detectable variation in performance was observed with regards to the input SOP of the polarized pump. This resilience to pump polarization variations can only be explained by the nearly complete depolarization of the intermediate 1455 nm Stokes component.

Regardless of the propagation direction, the DOP of the Stokes component at 1455 nm is below 20% at all considered gain levels when the DCF is used, whereas it is slightly higher in the SMF-based cavity, starting at 60% for 5 dB on-off gain and gradually reducing for higher on-off gains. Figure 3 shows the amplified signal DOP as a function of the on-off gain at the amplifier output, measured in forward and backward directions for both the fiber cavities under test, when the primary pump is fully polarized. A completely depolarized signal is only partially re-polarized through the polarization attraction phenomenon [20,21], whose efficiency is higher with FW pumping (see Fig. 3(a)). In contrast, the DOP of an initially polarized signal (see Fig. 3(b)) decreases with on-off gain due to the reduced DOP of the secondary pump. Similarly to the depolarized signal case, the effect of the pump on the polarization properties of the signal is stronger when pump and signal co-propagate along the cavity, whereas the signal DOP is only marginally affected by the backward propagating pump for on-off gain up to 20 dB.

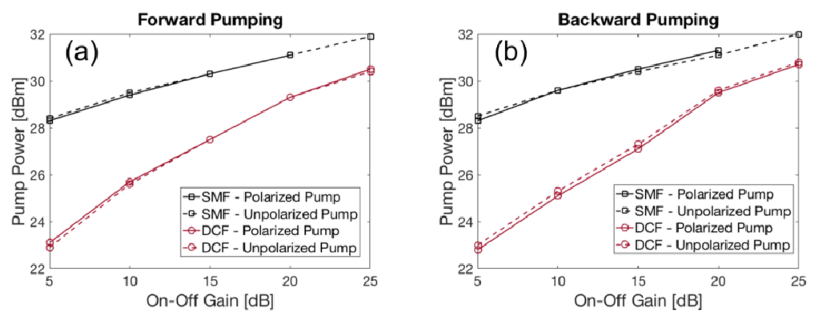

Fig. 4. Required pump power vs. signal On-Off gain, for a depolarized signal, using forward (a) and backward (b) 2nd order pumping in SMF (black, squares) and DCF (red, circles) fiber cavities. Continuous lines correspond to highly polarized pumps, whereas dashed lines correspond to fully depolarized ones.

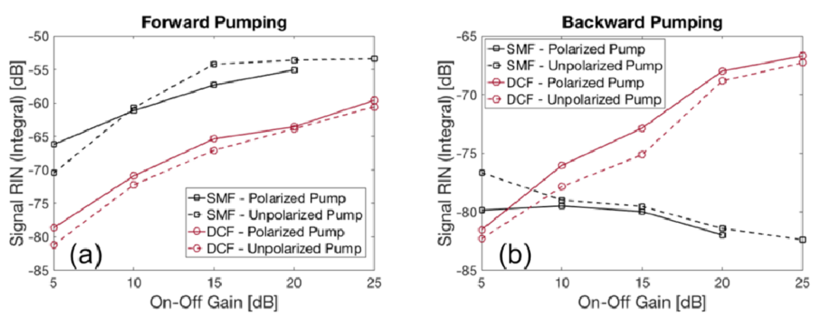

Fig. 5. Signal RIN vs. signal On-Off gain, for a depolarized signal, using forward (a) and backward (b) second-order pumping in SMF (black, squares) and DCF (red, circles) fiber cavities. Continuous lines correspond to highly polarized pumps, whereas dashed lines correspond to fully depolarized ones.

The amplifier behavior is exemplified in Figs. 4 and 5, which focus on the forward and backward pumped configurations respectively, with a fully depolarized 1550 nm input signal. In terms of gain, no appreciable difference can be observed between the performance of the fully polarized and the fully depolarized pumps neither in the SMF nor the DCF-based schemes. Regarding RIN, performances are again similar for the polarized and depolarized pumps, with a slight improvement in the measured integrated RIN when amplifying with a highly polarized pump in SMF fiber, and the opposite in the case of the discrete DCF-based amplifier.

We then studied the system using a fully polarized signal. Choosing a random pump SOP, performance is very similar to that attainable with a depolarized signal, but this time some benefits can be obtained by tuning the pump SOP, as shown in Fig. 6, where a slight improvement in the gain performance can be appreciated for a specific value of the pump SOP. Regarding output signal RIN (see Fig. 7), performance is again very similar for the polarized and depolarized pumps, except for the backward pumped 50 km SMF cavity, where at high gains an appropriate choice of the pump SOP can provide a performance improvement of up to 6 dB. Please note that pump depletion is higher in the 50 km SMF case, as fiber loss in the 1365 nm pump leads to an important unbalance between the FW and BW cavity-generated 1455 nm Stokes components. The increased depletion at higher gains leads to a saturation (for FW pumping) or even a decrease (for BW pumping) of RIN transfer, as first described in [22]. This is not noticeable in the 2 km DCF, where 1365 nm pump attenuation is very small across the cavity and the 1455 nm components are better balanced.

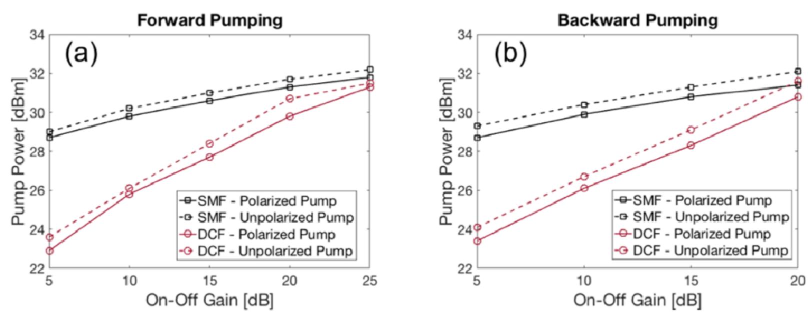

Fig. 6. Required pump power vs. signal On-Off gain, for a polarized signal, using forward (a) and backward (b) second-order pumping in SMF (black, squares) and DCF (red, circles) fiber cavities. Continuous lines correspond to highly polarized pumps, whereas dashed lines correspond to fully depolarized ones.

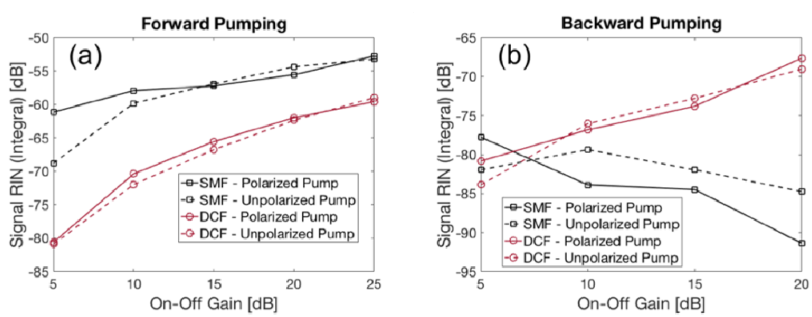

Fig. 7. Signal RIN vs. signal On-Off gain, for a polarized signal, using forward (a) and backward (b) second-order pumping in SMF (black, squares) and DCF (red, circles) fiber cavities. Continuous lines correspond to highly polarized pumps, whereas dashed lines correspond to fully depolarized ones.

In order to rule out potentially misleading results due to limited statistics, additional measurements were carried out for a different SMF fiber with even lower PMD, resulting in more efficient signal depolarization/repolarization [16], but similar results for integrated RIN transfer and pumping efficiency.

5. Conclusions

We have experimentally demonstrated that 2nd order ultralong cavity Raman fiber amplifiers pumped in the forward or backward direction are unaffected by polarization-dependent gain, both in terms of RIN generation and overall signal gain performance. This effect can be explained by the spontaneous depolarization of the laser-generated 1455 nm component at high gains due to gain saturation. Moreover, the use of highly polarized pumps in URFLs has been shown to offer slightly improved gain and RIN performance in some situations for long SMF cavities. Our results show that URFLs could be used in long-haul transmission in combination with highly polarized low-RIN semiconductor laser diodes without the need for polarization beam combining.

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Spanish MINECO grant TEC2015-71127-C2-1-R; Comunidad de Madrid grant S2013/MIT-2790-SINFOTON-CM.

References

1. S. Sergeyev, S. Popov, and A. T. Friberg, "Modeling polarization-dependent gain in fiber Raman amplifiers with randomly varying birefringence," Opt. Commun. **262**(1), 114–119 (2006).
2. C. Martinelli, L. Lorcy, A. Durécu-Legrand, D. Mongardien, and S. Borne, "Influence of Polarization on Pump-Signal RIN Transfer and Cross-Phase Modulation in Co-pumped Raman Amplifiers," J. Lightwave Technol. **24**(9), 3490–3505 (2006).
3. J. Ania-Castañón, "Quasi-lossless transmission using second-order Raman amplification and fibre Bragg gratings," Opt. Express **12**(19), 4372–4377 (2004).
4. M. A. Iqbal, M. Tan, L. Krzczanowicz, G. Rizzelli, F. Gallazzi, A. E. El-Taher, W. Forysiak, P. Harper, and J. D. Ania-Castañón, "Noise Performance Improvement of Broadband Distributed Raman Amplifier Using Dual Order Bidirectional Pumping," in *Asia Communications and Photonics Conference*, OSA Technical Digest (online) (Optical Society of America, 2016), paper AF4G.2.
5. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic University, 1995).
6. M. Krause, S. Cierullies, H. Renner, and E. Brinkmeyer, "Pump-to-Stokes RIN transfer in Raman fiber lasers and its impact on the performance of co-pumped Raman amplifiers," Opt. Commun. **260**(2), 656–661 (2006).
7. C. R. S. Fludger, V. Handerek, and R. J. Mears, "Pump to signal RIN transfer in Raman fiber amplifiers," J. Lightwave Technol. **19**(8), 1140–1148 (2001).
8. Y. Emori, S.-I. Matsushita, and S. Namiki, "Cost-effective depolarized diode pump unit designed for C-band flat-gain Raman amplifiers to control EDFA gain profile," in *Optical Fiber Communication Conference,* Technical Digest Postconference Edition. Trends in Optics and Photonics **Vol.37**, Baltimore, MD, USA, 2000, pp. 106–108.
9. C. Martinelli, L. Lorcy, A. Durecu-Legrand, D. Mongardien, S. Borne, and D. Bayart, "RIN transfer in co-pumped Raman amplifiers using polarization-combined diodes," IEEE Photonics Technol. Lett. **17**(9), 1836–1838 (2005).
10. R.-J. Essiambre, P. Winzer, J. Bromage, and C. H. Kim, "Design of bidirectionally pumped fiber amplifiers generating double Rayleigh Backscattering," IEEE Photonics Technol. Lett. **14**(7), 914–916 (2002).
11. V. E. Perlin and H. G. Winful, "Optimizing the Noise Performance of Broad-Band WDM Systems with Distributed Raman Amplification," IEEE Photonics Technol. Lett. **14**(8), 1199–1201 (2002).
12. S. K. Turitsyn, S. A. Babin, A. E. El-Taher, P. Harper, D. V. Churkin, S. I. Kablukov, J. D. Ania-Castañón, V. Karalekas, and E. V. Podivilov, "Random distributed feedback fiber laser," Nat. Photonics **4**(4), 231–235 (2010).
13. M. Tan, P. Rosa, S. T. Le, M. A. Iqbal, I. D. Phillips, and P. Harper, "Transmission performance improvement using random DFB laser based Raman amplification and bidirectional second-order pumping," Opt. Express **24**(3), 2215–2221 (2016).
14. M. Tan, P. Rosa, S. T. Le, V. V. Dvoyrin, M. A. Iqbal, S. Sugavanam, S. K. Turitsyn, and P. Harper, "RIN Mitigation and Transmission Performance Enhancement with Forward Broadband Pump," IEEE Photonics Technol. Lett. **30**(3), 254–257 (2018).
15. F. Chiarello, L. Ursini, L. Palmieri, and M. Santagiustina, "Polarization attraction in counterpropagating fiber Raman amplifiers," IEEE Photonics Technol. Lett. **23**(20), 1457–1459 (2011).
16. F. Chiarello, L. Palmieri, M. Santagiustina, R. Gamatham, and A. Galtarossa, "Experimental characterization of the counter-propagating Raman polarization attraction," Opt. Express **20**(23), 26050–26055 (2012).
17. J. D. Ania-Castañón, T. J. Ellingham, R. Ibbotson, X. Chen, L. Zhang, and S. K. Turitsyn, "Ultralong Raman Fiber Lasers as Virtually Lossless Optical Media," Phys. Rev. Lett. **96**(2), 023902 (2006).
18. G. Rizzelli, P. Rosa, P. Corredera, and J. D. Ania-Castañón, "Transmission Span Optimization in Fiber Systems with Cavity and Random Distributed Feedback Ultralong Raman Laser Amplification," J. Lightwave Technol. **35**(22), 4967–4972 (2017).

Optics EXPRESS

19. V. Karalekas, J. D. Ania-Castañón, P. Harper, S. A. Babin, E. V. Podivilov, and S. K. Turitsyn, "Impact of nonlinear spectral broadening in ultra-long Raman fibre lasers," Opt. Express **15**(25), 16690–16695 (2007).
20. M. Martinelli, M. Cirigliano, M. Ferrario, L. Marazzi, and P. Martelli, "Evidence of Raman-induced polarization pulling," Opt. Express **17**(2), 947–955 (2009).
21. V. V. Kozlov, J. Nuño, J. D. Ania-Castañón, and S. Wabnitz, "Theoretical study of optical fiber Raman polarizers with counterpropagating beams," J. Lightwave Technol. **29** (3), 341–347 (2011).
22. M. D. Mermelstein, C. Headley, and J.-C. Bouteiller, "RIN transfer analysis in pump depletion regime for Raman fibre amplifiers," Electron. Lett. **38**(9), 403–405 (2002).