Impact of nonlinear spectral broadening in ultra-long Raman fibre lasers

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Abstract: We present an experimental study of the impact of FWM-induced nonlinear spectral broadening on the effective reflectivity of ultra-long Raman fiber laser cavities of diverse lengths and fiber bases. We observe an exponential decay of the effective reflectivity with growing power. In standard single-mode fiber, effective reflectivity drops of up to 50% for shorter cavity lengths are observed, while the longest cavity length of 82.4km displays power leakage amounting to an effective reduction of reflectivity of approximately 30%. Using different types of fiber we examine the effect of chromatic dispersion on the Stokes wave broadening.

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1. Introduction

Stimulated Raman scattering (SRS) finds a very important application in the development of Raman fibre lasers (RFL). A typical RFL is a fiber resonator in which SRS shifts the spectrum of the radiation from a pump or series of pumps propagating through an optical fibre, towards lower frequency (~14 THz lower) Stokes components, which can be trapped in the fibre with the help of fibre Bragg grating (FBG) reflectors. The Stokes radiation is sometimes used as a Raman pump itself in a multi-cavity cascading process [1]. RFLs are photonic devices with great commercial potential in a variety of practical cases, as their tunability, compactness, and capability for multi-wavelength operation makes them attractive CW sources in applications such as long-distance remote sensing [2], optical tomography [3], supercontinuum generation [4] or as high power pump sources for distributed Raman amplified telecommunication systems, (see [5] and references therein), to name but a few.

An important characteristic of RFL sources is that the spectrum of the generated Stokes wave typically exhibits four-wave mixing (FWM)-induced nonlinear broadening [6] due to its propagation through the fibre cavity. In ideal circumstances, the generated radiation would be perfectly trapped inside the cavity formed by the two FBGs positioned at both of its ends. In most practical cases, though, the radiated spectrum is broadened beyond the bandwidth of the FBGs, resulting in leakage of laser power from the cavity which has an impact on the RFL's performance, degrading its quality. In particular, as it was demonstrated in [7], the "effective" reflectivity of the FBGs decreases proportionally with increasing total power in the cavity, and hence with the amount of broadening of the first-Stokes wave.

Recently, the concept of Raman fibre lasers with ultra-long cavities of tens of km (URFL) was proposed and experimentally demonstrated [8, 9], and their application to quasi-lossless transmission in fibre optic communication links explored [8-10]. In such long lasers, the combined forward- and backward- propagating power generated inside the cavity at the 1455 nm Stokes wavelength experiences reduced variation along the fibre span. Hence, it can be used as a secondary pump to provide a near constant Raman gain for an optical signal propagating around 1550 nm. Using this scheme, quasi-lossless transmission over 75km with near-flat gain response over a bandwidth of 36nm was demonstrated [10]. The operation of URFL can be described [8, 9] by a set of steady-state coupled equations corresponding to each of the pumps as well as the co and counter-propagating 1455nm waves, and including all relevant mechanisms in addition to SRS, such as double Rayleigh scattering and amplified spontaneous emission.

As it is to be expected from the cavity length and has been recently demonstrated [11], this new class of lasers features a huge number of resolvable cavity modes (~10^8 for the longer cases), which enhances the effect of spectral broadening of the radiation through turbulent-like FWM modal interaction [12]. In this Letter we perform an experimental and numerical study on the impact of nonlinear spectral broadening on the efficiency of URFLs with cavity lengths varying from several km up to a maximum length of 82.4km.

2. Experimental setup and procedure

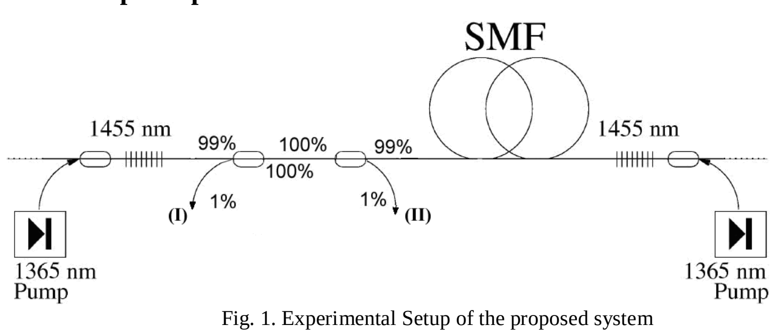

Fig. 1. Experimental Setup of the proposed system

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The basic design of an ultra-long Raman laser cavity is schematically depicted in Fig. 1. The system consists of two equal-power depolarized pumps centred at 1365nm and launched from both ends of a standard-single mode fibre (SMF) span. Two FBGs with high reflectivity (~99%), centred at 1455nm and with a bandwidth of ~1nm, are positioned at either ends of the fibre span forming a high-Q cavity trapping the 1455nm generated waves. When the total power from the primary pumps is above the required threshold for SRS-induced gain to overcome fibre attenuation at the Stokes wavelength, the cavity starts lasing at 1455 nm. In order to study the dependence of effective reflectivity with the injected primary pump power and cavity length, different fibre spans were considered. In particular, SMF fibre reels with lengths of 6.6, 10.1, 21, 40, 50.8 and 82.4km of SMF where utilized.. The intra-cavity generated first-Stokes wave was measured via two 99:1 splitters placed between the first reflector and the fibre span, as it is illustrated in Fig. 1. The 1% splitter outputs were positioned facing opposite directions in order to allow for the simultaneous monitoring of both the incident and reflected first-Stokes wave components via ports (I) and (II) respectively, with the use of a two-port switch. In this way we ensured that the experimental parameters were not affected by the switching between monitoring directions. The 1455nm spectra corresponding to the waves ‘incident to’ and ‘reflected from’ the grating were captured using a high resolution (~0.01nm) optical spectrum analyzer, and the powers were measured with a power meter for high accuracy.

3. Results and discussion

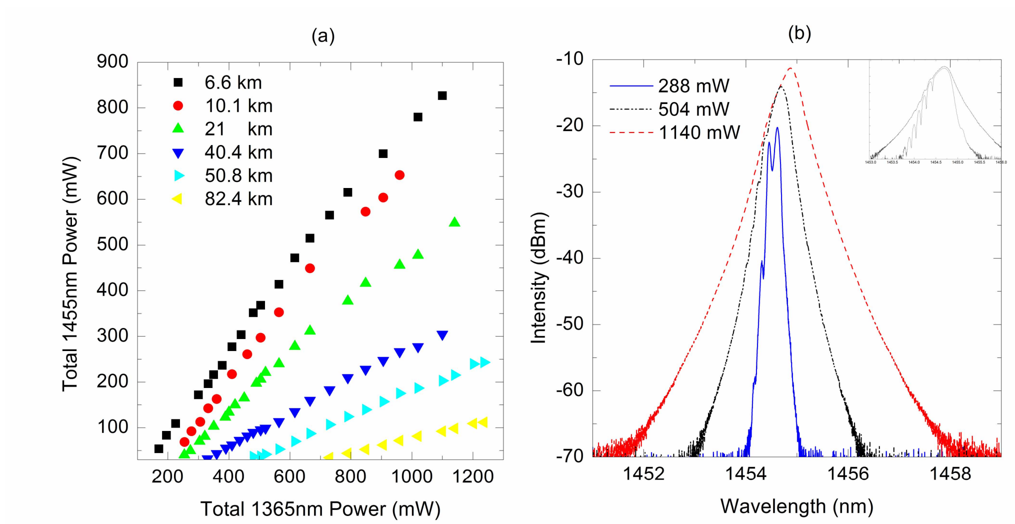

Fig. 2. (a) Total 1455nm intra-cavity power as a function of the total 1365nm input pump power for all of the studied lengths. (b) Spectral evolution of the 1455nm Stokes spectrum in a 21km cavity for the input power of 288, 504 and 1140mW. The inset plot presents the reflected (inner) and incident (outer) spectra for 504mW of pump power.

Results showing clear signs of spectral broadening on the generated 1455nm wave are presented in Fig. 2. In more detail, Fig. 2(a) depicts the dependence of the total 1455nm power as a function of the total injected 1365nm primary pump power for all of the studied lengths. Please note that the total 1455nm power presented is defined here as the summation of the total incident and reflected power at the grating, obtained by measuring at points (I) and (II) in Fig. 1. For identical pump powers, the total 1455nm power is lower for longer span lengths due to increasing cavity losses. This results also in higher threshold values for the 1365nm pump. Fig. 2(b) presents the spectral evolution of the 1455nm first-Stokes component incident to the FBG for a 21km cavity with three different input pump powers. The spectra show clear signs of broadening with increasing 1365nm pump power. At low pump powers, the narrow spectrum is asymmetric, with ripples that can be directly attributed to the reflection

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profile of the FBGs used to form the cavity. As the 1365nm pump power is increased, these ripples are washed out and the spectrum acquires clear exponential tails. The insert in Fig. 2(b) shows the 1455nm wave spectra taken at ports (I) and (II) for 504mW of total pump power. The spectrum at port (I) (the broader one) is the 1455nm signal incident to the FBG under investigation. As it can be observed the wave has undergone significant spectral broadening within the laser cavity and shows no signs of the previously visible ripples from the reflection profile of the FBG. On the other hand, the spectrum taken at port (II) (the narrower one) exhibits the characteristic ripples due to the recent reflection at the FBG. One other important feature of the 21km cavity spectra as presented in Fig. 2b is the drift towards longer wavelengths with increasing pump power. We have observed that this drift is not related to any nonlinear effects suffered by the 1455nm component during propagation through the cavity and is instead caused by the shift of the central wavelength of the cavity gratings, which is directly related to the total amount of power at the FBG, strongly suggesting thermal expansion as the cause.

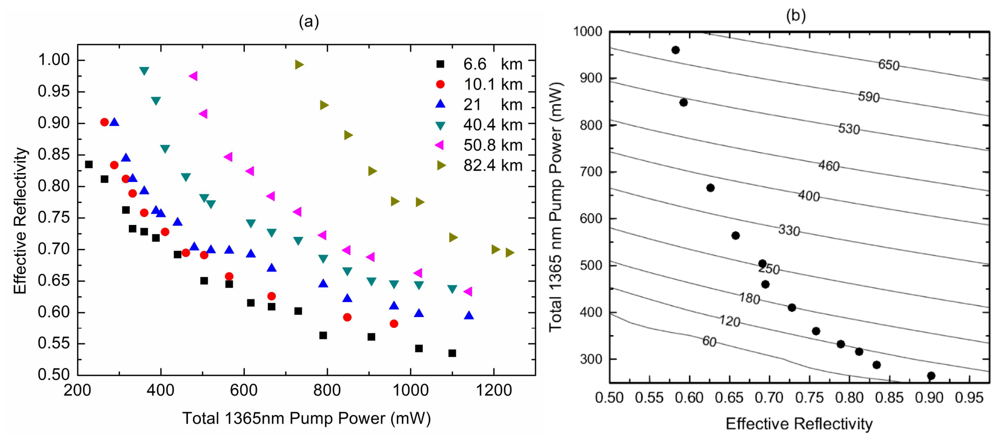

Fig. 3. (a) Effective cavity reflectivity as a function of the total 1365nm pump power for 6.6, 10.1,21, 40.4, 50.8, 82.4km cavities. (b) Numerical contour plot for a 10km cavity, showing iso-lines of identical total 1455nm power vs. pump power and effective reflectivity. The dots represent superimposed experimental results.

The reflectivity of the FBG mirror is given by the ratio of the reflected power to the incident wave power. Having measured these quantities for different pump powers and lengths, we present in Fig. 3(a) curves showing the dependence of the effective reflectivity on the total injected 1365nm power and hence proportionally on the amount of nonlinear broadening induced in the 1455nm component. It is clearly observed that the effective reflectivity decays rapidly as the total 1365nm pump power increases, compromising the laser efficiency at high pump powers. One interesting conclusion to be drawn from the results displayed on Fig. 3(a) is that the effective reflectivity is less affected by high pump powers in a longer cavity, which suggests that despite the short cavity length, accumulated nonlinearity is higher in the shorter cavities. Based on the above observation we can say that longer cavities of the kind more likely to be applied for long-distance communications will probably not be affected by the nonlinear broadening as long as the transmission system is operated in a linear regime, that is, low signal powers are used, imposing low pump power requirements. On the other hand, when working with shorter links with potential applications in nonlinear optical processing (and hence potentially requiring high pump powers), it becomes unavoidable to take into account the impact of nonlinear broadening, as it can lead to important power leakage unless FBGs with an unusually broad and flat reflectivity profile are used.

In the conducted experiments with standard SMF, for the case of longer lengths, the effective reflectivity of the FBGs was reduced just below 70% for the highest pump powers achieved. In shorter cavities, the impact of nonlinear broadening was more evident, resulting

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on a decrease in the effective reflectivity by 50%. As shown in Fig. 3(a) the reflectivities experience in all cases an exponential-like decay with increasing injected pump power. Figure 3(b) illustrates the effect on URFL links efficiency of the power leakage, by superimposing the experimental measurements of effective reflectivity vs. pump power, corresponding to a 10.1km long cavity, on top of the numerical contour plot, obtained by solving the steady-state equations of the laser [8], depicting the evolution of the lines of equal 1455nm power on the pump power - effective reflectivity plane for the same 10.1 km cavity. The numerical iso-lines are in good agreement with the measured total 1455nm power at the experimental points, and give us a visual idea of the impact of decreasing effective reflectivity on the power efficiency of the URFL, showing how the leakage caused by nonlinear broadening makes it necessary to increase 1365nm pump power in order to reach the same total 1455nm power.

A possible solution to reduce the impact of nonlinear broadening would be to use fibre Bragg gratings with a wider reflection band (e.g. chirped fibre Bragg gratings). Although a wider grating bandwidth would in principle allow for even further broadening of the Stokes wave, it should also prove to be more resistant to effective reflectivity degradation, hence reducing power leakage, with the additional advantage of potentially improving signal gain flatness over a certain bandwidth [13].

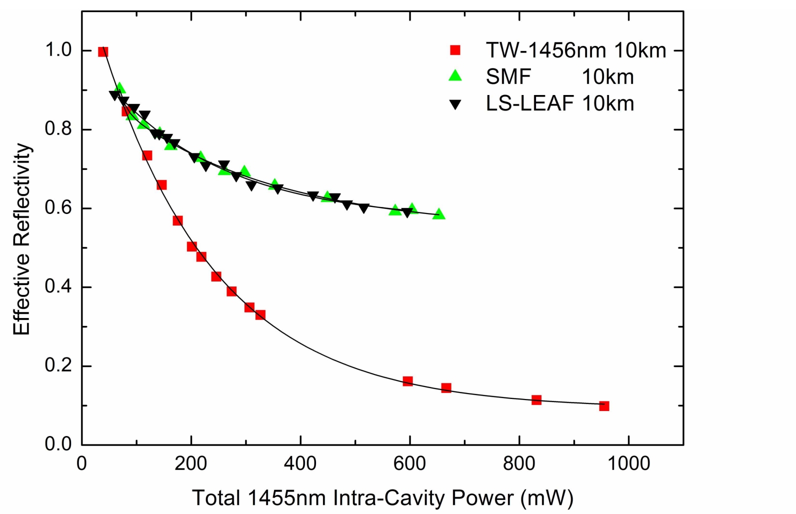

Fig. 4. Effective reflectivity as a function of total 1455 Stokes power for 10km of TrueWave-RS, LS-LEAF, and SMF. Solid lines represent exponential fit.

Another very important factor that must be taken into account when designing an ultra-long laser for maximum efficiency is fiber dispersion, more specifically the proximity of the Stokes wavelength to the zero-dispersion wavelength (ZDW) of the fiber. This is illustrated by the results in Fig. 4, which compares the exponential decay of the effective reflectivity as total intra-cavity power increases, for three similar lengths (~10 km) of different fiber bases (standard SMF, LEAF and Truewave fiber). Despite all three fibers having a comparable nonlinear coefficient, reflectivity drops much faster with power for the Truewave fiber laser, for which the lasing wavelength lies very close to the ZDW of 1454 nm, but still in the anomalous dispersion regime. Modulation-instability induced nonlinear broadening, coupled with the enhanced FWM processes thanks to more efficient phase matching, greatly reduce the effective reflectivity at high powers. On the other hand, LEAF and SMF, for which the lasing wavelength lies more than 100 nm away from the ZDW, show responses that are nearly identical to each other, with much lower nonlinear broadening than Truewave.

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The strong dispersion-dependent response of the Stokes wave broadening in the cavity stresses the need for a careful choice of the most convenient fiber for each different possible application of the URFL. In the case of broadband transmission, an appropriate combination of fibre dispersion and grating bandwidth could provide, for example, a moderate nonlinear broadening of the Stokes wave for increased gain flatness, while still preserving an adequate laser efficiency. On the other hand, when dealing with nonlinear signal processing applications, for which the choice of fiber dispersions at the signal wavelength will be constrained, the use of specifically tailored, dispersion-engineered fibers could provide an additional degree of freedom to optimize system performance.

4. Conclusion

We have experimentally demonstrated the power dependence of spectral broadening in ultra-long fibre Raman lasers with cavity lengths up to 82.4 km. Broadening of the radiation beyond the bandwidth of the cavity gratings leads to power leakage out of the fibre resonator and to additional power-dependent loss that can formally be treated as a reduction (approximately exponentially dependent on power) of the effective reflectivity of the FBGs. Even when operating at Stokes wavelengths well separated from the fiber ZDW, we have shown that this effective reflectivity can be reduced to about 50% for gratings with a ~ 1nm bandwidth in the case of short URFL cavities and up to 70% for a longer 82.4 km cavity. Nonlinear pump broadening thus has to be carefully taken into account when designing URFL for nonlinear optical processing applications, in which the combination of short cavity lengths and high pump powers could lead to important degradation on the cavity quality. The impact of nonlinear broadening is less likely to have a dramatic effect on the performance of longer URFL with applications in long-distance communications, but it should be considered as a potentially deleterious factor nonetheless.

If the laser Stokes wavelength falls close to the ZDW of the cavity fiber, nonlinear broadening is greatly enhanced, and effective reflectivity deteriorates much faster with power, being reduced to just 10% at maximum pump power in a 10 km Truewave fiber cavity.

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