

## **Low cost incoherent pump solution for Raman fiber amplifier**

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In this work, we demonstrate the implementation of a low cost broadband pump source for Raman amplification. The advantages of this incoherent pumping scheme were demonstrated by comparing, experimentally and numerically, this solution with the one based on coherent pumping. We observed a decrease by 1.4 dB in the Raman gain ripple and a 16% increase in the bandwidth, for the latter solution.

Keywords: Raman fiber amplifier, incoherent pump.

### **1. Introduction**

One of the most important challenges to the design of Raman fiber amplifiers (RFA's) is that of achieving a flat gain profile over a broad wavelength band, at a reasonable cost of implementation [1]. Typically, multiple pumps at different wavelengths are used to induce a flat gain in an ultra-wide bandwidth. In this type of amplifiers, the expected gain peak is shifted by 13.2 THz ( $\approx 100$  nm in this spectral region) with respect to the pump signal frequency.

Another option to enlarge the bandwidth of Raman amplifiers makes use of incoherent pumps. This approach has recently been proposed and the first experimental performance results show a 7 dB on/off gain with a gain ripple of approximately 0.8 dB over all the C spectral band [2].

Later numerical studies corroborate the above experimental results. They have also shown that the number of pumps needed to obtain the same gain flatness can be significantly reduced using incoherent pumping [3–5].

In addition, incoherent pumping has also the advantage of reducing nonlinear effects such as stimulated Brillouin scattering or four wave mixing induced by the pump-to-pump, pump-to-signal and pump-to-noise interaction [6].

The last reported studies on Raman incoherent amplification have focused on numerical simulations and they have mainly concerned the design of optimum pump spectra for the purpose of minimizing the gain ripple. The best results achieved were 20 dB on/off Raman gain over a 70 nm bandwidth with a gain ripple better than 0.1 dB [7, 8]. Earlier results also indicate that incoherent pumping decreases the spectral ripple of the Raman gain [9–11].

In this paper, we report the implementation of an RFA solution based on commercially available pumps adapted for incoherent emission. Also, we implemented a computational model in order to estimate the performance for this amplification technology. The gain and noise figure profiles of the counter pumping architecture were analyzed experimentally and numerically.

## 2. Raman amplification model

The theoretical model used to describe the implemented experimental system was based on the following set of coupled differential equations, which describe a multi-pump Raman amplifier, considering the pump-to-pump, pump-to-signal, and signal-to-signal interactions, the attenuation and the temperature dependent amplified spontaneous emission (ASE) [12, 13]:

$$\begin{aligned} \pm \frac{dP_k^\pm}{dz} = & -\alpha_k P_k^\pm + P_k^\pm \sum_{j=1}^{k-1} \frac{g_r(\Delta \nu_{j,k})}{A_{\text{efc}} k_p} (P_j^\pm + P_{\text{ASE},j}^+) + \\ & - P_k^\pm \sum_{j=k+1}^N \frac{\nu_k}{\nu_j} \frac{g_r(\Delta \nu_{k,j})}{A_{\text{efc}} k_p} (P_j^\pm + P_{\text{ASE},j}^+) + \\ & - P_k^\pm \sum_{j=k+1}^N \frac{\nu_k}{\nu_j} \frac{g_r(\Delta \nu_{k,j})}{A_{\text{efc}} k_p} 4h\nu_k \Delta\nu \eta_{j,k}(T) \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{dP_{\text{ASE},k}^+}{dz} = & -\alpha_k P_{\text{ASE},k}^+ + P_{\text{ASE},k}^+ \sum_{j=1}^{k-1} \frac{g_r(\Delta \nu_{j,k})}{A_{\text{efc}} k_p} (P_j^\pm + P_{\text{ASE},j}^+) + \\ & - P_{\text{ASE},k}^+ \sum_{j=k+1}^N \frac{\nu_k}{\nu_j} \frac{g_r(\Delta \nu_{k,j})}{A_{\text{efc}} k_p} (P_j^\pm + P_{\text{ASE},j}^+) + \\ & - P_{\text{ASE},k}^+ \sum_{j=k+1}^N \frac{\nu_k}{\nu_j} \frac{g_r(\Delta \nu_{k,j})}{A_{\text{efc}} k_p} 4h\nu_k \Delta\nu \eta_{j,k}(T) + \\ & + \sum_{j=1}^{k-1} \frac{g_r(\Delta \nu_{j,k})}{A_{\text{efc}} k_p} 2h\nu_k \Delta\nu (P_j^\pm + P_{\text{ASE},j}^+) \eta_{j,k}(T) \end{aligned} \quad (2)$$

where  $P_k, P_{\text{ASE}, k}$  denotes the power of the  $k$ -th pump or signal, ASE noise at frequency  $\nu_k$  propagating in the  $\pm z$  direction.  $h$  represents the Planck constant,  $\alpha$  the fiber attenuation,  $A_{\text{efc}}$  the optical fiber effective area,  $k_p$  is a constant that takes into account the contribution for the signal polarizations and  $\eta(T)$  is a phonon occupancy factor.  $\Delta\nu$  is the frequency detuning between the pump and signal. In this model, the effect of single Rayleigh backscattering and anti-Stokes generation are neglected. When considering an incoherent pump source, which spectrum could be approximated by a large number of coherent pumps, spread over the spectral bandwidth of the incoherent signal, the effect induced by this scheme is equivalent to the utilization of multipumps.

The experimental values used for the fiber Raman gain coefficient  $g_r$  were taken from earlier experimental results reported in references [14, 15]. The remaining system parameters are also based on data previously used in simulation scenarios:  $\alpha = 0.2$  dB/km,  $k_p = 2$ ,  $\eta(300 \text{ K}) = 0.1226$  and  $A_{\text{efc}} = 80 \mu\text{m}^2$  [16].

Another simplification relies on neglecting the signals and pump spectral shape. The incoherent pump was modeled as a multi-pump Raman amplifier composed of a large number of pumps (100 is considered sufficient) with infinitesimal spectral width.

Our analysis of the RFA performance focuses on the on/off gain  $G_{\text{on/off}}$  and effective noise figure  $\text{NF}_{\text{eff}}$ , which are respectively defined as:

$$G_{\text{on/off}} = 10 \log \left( \frac{P_{s, \text{pump on}}}{P_{s, \text{pump off}}} \right) \quad (3)$$

$$\text{NF}_{\text{eff}} = 10 \log \left[ \frac{1}{G_{\text{on/off}}} \left( \frac{2P_{\text{ASE}}}{h\nu\Delta\nu} + 1 \right) \right] \quad (4)$$

where  $P_s$  is the signal output power,  $P_{\text{ASE}}$  the forward ASE noise output power, measured in a bandwidth of  $\Delta\nu$ , for a signal with frequency  $\nu$ .

### 3. Description of the experiment

The RFA performance was accessed measuring the Raman on/off gain and the effective noise figure for the counter pumping configuration with coherent and incoherent pumps.

The coherent pumping source used was a high power fiber Bragg grating (FBG) stabilized laser, peaking at 1489 nm (FITEL model-FOL1425RUX-617). The incoherent pump was obtained also from a high power FBG pump laser, where the stabilization grating was removed, causing an emission spectrum with a full width at half maximum (FWHM) of 10 nm, centred at 1498 nm. The pump power was set to achieve the same Raman gain average for both pumps, which implies a pumping power of 160 mW for the coherent pump and 155 mW for the incoherent one. Figure 1 shows optical spectra for the two pumps (coherent and incoherent).

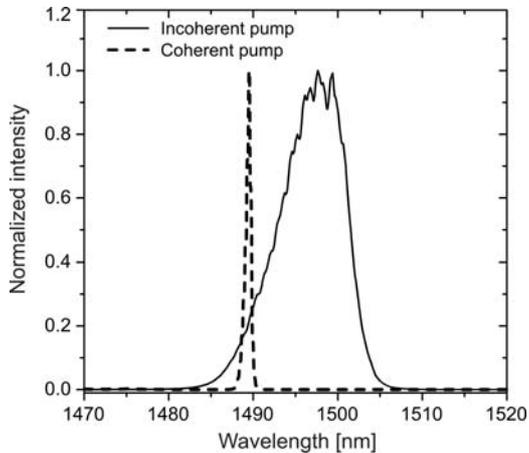


Fig. 1. Normalized optical spectra for the coherent and incoherent pumps, measured with a 1 nm optical resolution.

The transmission was analyzed for 21 signals 2 nm spaced, over the 1580–1620 nm spectral region, with an optical power of  $-5$  dBm per signal. For amplification/propagation medium a 40 km standard single mode fiber was used.

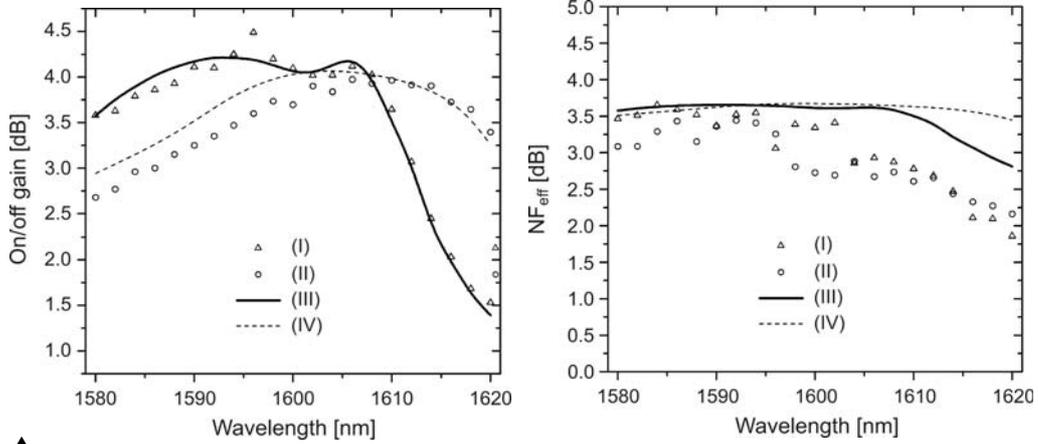
The implemented experimental setup was based on the typical schemes of counter pumping Raman amplification [13]. The signals and pumps were joined by a backward pump isolator (DICON), and an optical isolator was placed just before the fiber to protect the signal source. The signal analyses were carried out with an optical spectrum analyser (OSA) (Advantest Q8384).

#### 4. Results and discussion

The implemented amplification scheme achieved a gain average of 3.55 dB for both the incoherent and coherent pumping over the spectral range considered. Figure 2 displays the experimental and simulated gain spectra for the two pumping configuration schemes showing that the simulation results are in good agreement with experimental ones. The average values for the reduced chi-square between the experimental and simulated results are 0.09 and 0.18 for the coherent and incoherent pumps, respectively.

Moreover, Fig. 2 clearly shows a flatter gain spectrum for incoherent pumping over the spectral range considered. The gain spectrum maximum ripples are equal to 1.97 dB and 0.82 dB for coherent and incoherent pumps, respectively. The ripple was calculated in relation to the average gain value and measured over a  $-0.5$  dB bandwidth. The numerical simulation also corroborates these results and shows a 1.4 dB decrease in the ripple value for the incoherent pumping scheme, compared to the coherent one.

The experimental effective noise figures for both pumping schemes are depicted in Fig. 3 in addition to the corresponding simulation results. The simulation results are in good agreement with the experimental ones.



▲ Fig. 2. Experimental (points) and simulated (lines) data for the on/off gain with coherent pumping (I, III) and incoherent pumping (II, IV).

Fig. 3. Experimental (points) and simulated (lines) effective noise figures with coherent pumping (I, III) and incoherent pumping (II, IV).

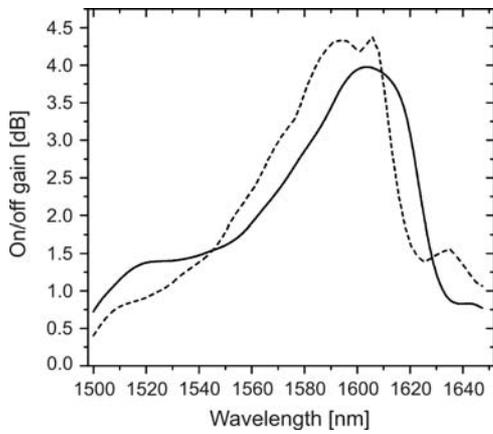


Fig. 4. Simulated on/off gain for incoherent pumping (I) and coherent pumping (II).

Considering good performance of the computational model in describing the experimental data, we attain the total Raman gain bandwidth making use of simulated results, as presented in Fig. 4.

The gain bandwidth at  $-1$  dB is 34 nm for the coherent pump and 39 nm for the incoherent one. At  $-3$  dB the gain bandwidths are 102 nm and 118 nm for the coherent and incoherent pumps, respectively. It is evident that incoherent pumping makes the Raman amplification bandwidth increase by 16%, as predicted theoretically.

## 5. Conclusions

We have tested a low cost Raman amplification scheme with an incoherent pump source. We have also implemented a numerical simulation algorithm for coherent and incoherent pumping.

Our results confirmed the advantages of incoherent pumping, such as a decrease of the spectral gain ripple and an increase in the amplification bandwidth.

Furthermore, a good agreement between the experimental and simulation results confirmed the accuracy of the computational model.

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