Pump-to-Stokes relative intensity noise transfer in Brillouin amplifiers

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Abstract *This paper proposes for the first time an analytical expression of the relative intensity noise (RIN) transfer in Brillouin amplifiers. Theoretical modelling and experimental measurements have been performed in the case of narrow linewidth pump.*

Introduction

Stimulated Brillouin scattering (SBS) has been widely investigated in optical sensors, fibre lasers [1,2], slow light applications [3] and narrow-band filter realizations [4]. The two major sources of noise in SBS process are: the spontaneous amplified emission (ASE) and the pump-to-Stokes relative intensity noise (RIN) transfer. RIN transfer has been thoroughly studied in Raman amplifiers [5], whereas in Brillouin amplification, most of the research on noise performance is up to now focused on ASE. For RIN transfer in SBS, there have been literatures on RIN transfer in Brillouin lasers [1-2]. However, there have paid little attention on the impact of RIN transfer on the performance of SBS amplifiers, which are usually used to induce slow light propagation.

In this paper, we study the RIN transfer in SBS pumped by narrow band pump. We firstly propose to address the problem with a frequency domain model. Afterwards, an analytical expression is derived to characterize the RIN transfer in the pump undepletion regime. This expression can be used to study the Brillouin amplifiers with broadband pump. Experimental measurements are performed by using a monochromatic pump modulated by an electrical sinusoidal generator. Study on RIN transfer both in the pump depletion and undepletion regimes show an excellent agreement between the experimental measurements and theoretical predictions.

Theoretical model

The RIN transfer in Brillouin amplifiers can be characterized by following frequency domain model, which is derived from the temporal domain one [6]:

$$-\frac{\partial \Delta\tilde{E}_p}{\partial z} - i\omega\frac{n_g}{c}\Delta\tilde{E}_p = -\frac{\alpha}{2}\Delta\tilde{E}_p - \frac{g_B}{2A}\Delta\tilde{E}_s Q - \frac{g_B}{2A}E_s\Delta\tilde{Q}$$

$$\frac{\partial \Delta\tilde{E}_s}{\partial z} - i\omega\frac{n_g}{c}\Delta\tilde{E}_s = -\frac{\alpha}{2}\Delta\tilde{E}_s + \frac{g_B}{2A}\Delta\tilde{E}_p Q^* + \frac{g_B}{2A}E_p\Delta\tilde{Q}^*$$

$$\Delta\tilde{Q} = \frac{\frac{\Gamma_B}{2}\Delta\tilde{E}_p E_s^* + \frac{\Gamma_B}{2}E_p\Delta\tilde{E}_s^*}{\frac{\Gamma_B}{2} - i(\omega + \Delta\omega)} \qquad (1)$$

We treat the noise term on the pump as a small perturbation and the resulting space and frequency dependant amplitudes fluctuations are denoted as $\Delta\tilde{E}_p(z,\omega)$, $\Delta\tilde{E}_s(z,\omega)$ and $\Delta\tilde{Q}(z,\omega)$ The fluctuations are small as compared with the steady state amplitudes $E_p(z)$, $E_s(z)$ and $Q(z)$. The model is based on the perturbation theory, which neglects the high order terms o (Δ^2).

The solution of (1) can be obtained analytically by neglecting the pump depletion:

$$\frac{\Delta\tilde{E}_s(L)}{E_s(L)} = kG(L)\ x$$

$$\int_0^L\left(\frac{k'}{k}\Delta\tilde{E}_p E_P^* + E_p\Delta\tilde{E}_p^*\right)G(z)^{-1}\exp\left(i\omega\frac{n_g}{c}(L-z)\right)dz$$

(2)

where:

$$G(z) = \exp\left((k-k')P_p Z_{eff}\right) \qquad (3)$$

$$Z_{eff} = \frac{1-\exp(-\alpha z)}{\alpha} \qquad (4)$$

$$k' = \frac{g_B}{2A}\frac{\Gamma_B/2}{\Gamma_B/2 + i\Delta\omega} \qquad (5)$$

where L is the fiber length, z is the distance from the local fiber point to the fiber input.

The RIN transfer function is defined as $10\log(r_s/r_p)$, where $r = (\Delta P/P)^2$. From (2), we can see that the RIN transfer function is a pseudo-periodical function, and the local minimal frequencies for the RIN transfer function are given by:

$$f_n = \frac{NV_g}{2L} \qquad (6)$$

where N is a integer and V_g is the group velocity,.

Experimental setup

The RIN transfer in SBS amplifier pumped by a narrow spectral linewidth diode is measured. The experimental setup is illustrated in Fig. 1. Truewave fibres with the length of 300-m and 20-km are used as the gain media. A monochromatic tunable diode at 1548-nm is used as the light source, whose power is divided by a coupler. Part of the power is used as the pump, which is modulated using a Mach-Zehnder modulator driven by the electrical sinusoidal generator of a network analyzer (HP 4194A ranging 0.1-Hz~100-MHz). A high power EDFA is used to amplify the pump before its launching into the fibre. The other part of the diode power is modulated by another Mach-Zehnder modulator driven by a signal generator generating a 10.764-GHz sinusoidal wave, corresponding to the Brillouin gain peak in Truewave fibre. The modulated light is then filtered by an optical filter with 0.1nm bandwidth. The filtered side-band is used as the input signal and its power is –20-dBm. An optical circulator is placed at the fiber output to extract the signal counterpropagating with the pump. Two polarization controllers are placed after the pump and signal laser sources to optimize the output power. The output signal is detected by a photodetector and the RIN transfer function is measured by the network analyzer.

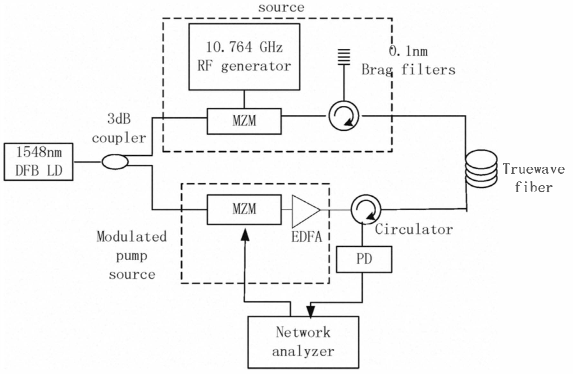

Fig. 1. Experimental setup for measurement of the Brillouin amplifier RIN transfer function

Results and discussions

The RIN transfer function of the 300-m Truewave fibre is shown in Fig. 2. The input pump power is 14-dBm. The comparison between the measurements and theoretical results shows excellent agreement. It is also shown that counter propagation averages the noise over the fibre, creating the extinction of 20-dB per decade at high frequency, just as an electrical low pass-filter does. The cut-off frequency results from the Brillouin gain bandwidth and from the walk-off effect. Substituting N=1, L=300-m into the Eq. (6), the first dip frequency is about 300-KHz, which exactly agrees with Fig. 2. The frequencies of the dips are not dependent on the pump power changes.

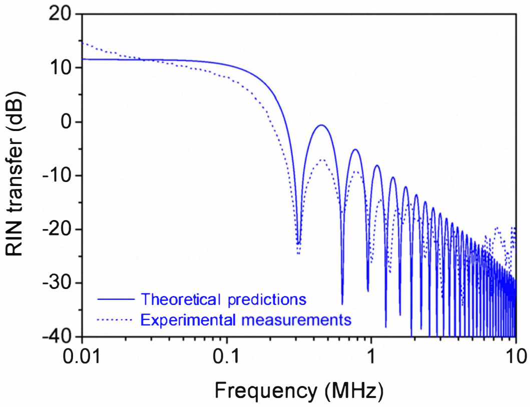

Fig. 2 RIN transfer in 300 m Truewave fibre

In Fig.3, RIN transfer with different pump powers for a fibre length of 20-km is presented. The RIN transfer has been measured for the 2-dBm and 10-dBm pump power respectively. When the pump power is 2-dBm, the RIN transfer decays exponentially when the frequency increases. The overall trends between the theoretical and experimental curves are identical, but the dips in the experimental curves are not results of the phase mismatch between the pump and Stokes wave. According to Eq. (6), the dips resulting from the walk-off effect are too close to be observed. For longer fibre, Brillouin threshold is rather lower than the short fibre and hence it is easier for the pump to reach the Brillouin threshold and to be saturated. From the figure, we can see that when the input power is 10-dBm, the gain is already saturated and the RIN transfer does not increase along with the increase of the pump power, which is consistent with the numerical simulation presented in [7]. When the gain is fully saturated, a RIN transfer reduction due to the depletion of the pump power and the decrease of the effective fibre length can be observed.

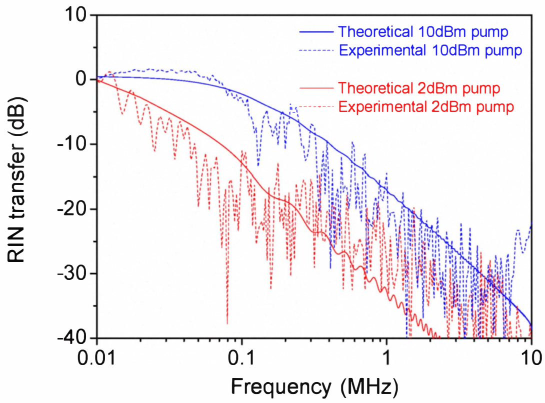

Fig. 3 RIN transfer in 20 km Truewave fibre

Conclusions

We have studied the pump-to-signal RIN transfer in SBS amplification. Based on the frequency domain model, an analytical expression is derived in the pump undepletion regime. For broadband SBS slow light experiment, the pump distributes in the broad spectrum and hence works in the undepletion regime. Experimental demonstrations have been performed with a 300-m and a 20-km fibre. The measurements have shown excellent agreement with theoretical predictions both for the pump depletion and undepletion regimes.

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