Modulation Instability with delayed nonlinear effects in Raman fiber amplifiers

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The coupling between two optical waves in a nonlinear medium leads to a wide variety of fascinating effects. Distributed Raman amplification (DRA), four-wave mixing (FWM), and modulation instability (MI) are the most important ones with implications on the fiber communication systems. DRA is particularly attractive amplification process for use in the fiber-based communication systems. It employs the Raman scattering (light scattering from molecular vibrations) in the same fiber, used for the transmission of data. The wide amplification range (see Fig.1), fast time response (tens of femtoseconds), and high gain are the most important characteristics of DRA.

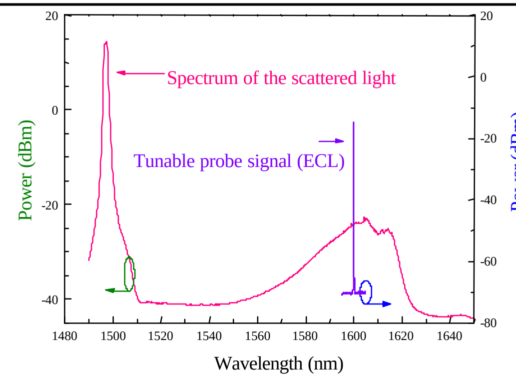


Fig.1 Spectral characteristics of the Raman amplification

We investigate the development of modulation instability in Raman fiber amplifiers. The frequency dependence of the experimentally observed spectral broadening reveals the influence of the two-beam coupling, resulting from the time-delayed Raman part of the third-order nonlinear susceptibility.

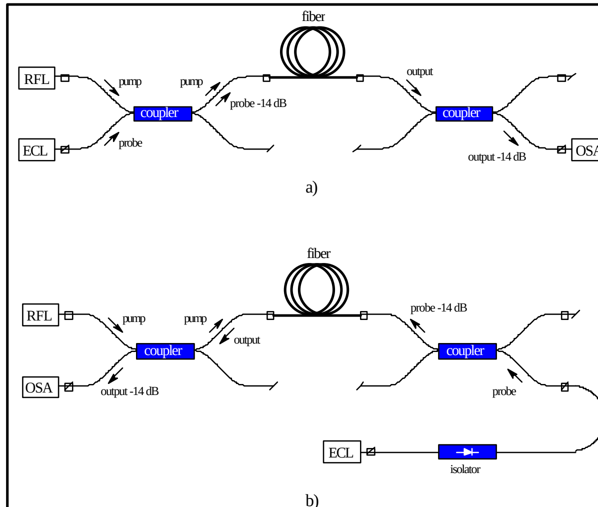
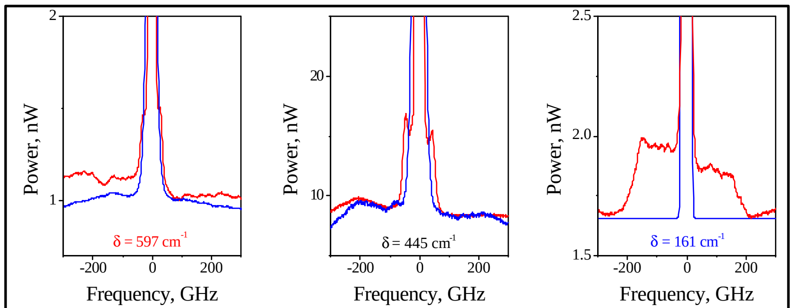
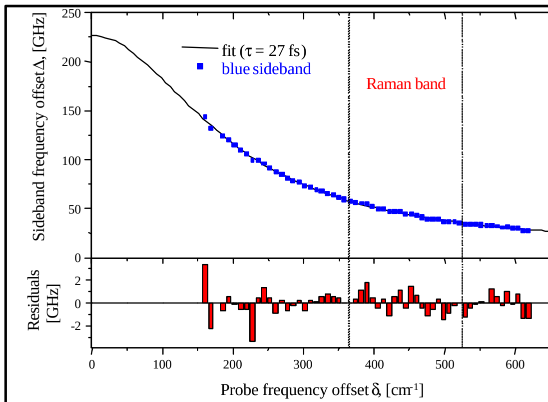


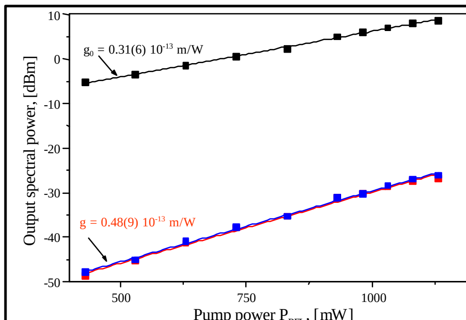
Fig.2 Experimental setup. a) forward pumping; b) backward pumping



Broadened spectra after Raman amplification in 25 km of Allwave fiber (red) and 20 km of Truewave fiber (blue) for three probe frequency offsets. Sideband frequency shift Δ depends on the probe frequency offset δ. No sideband observed in the case of Truewave fiber, as well as in backward-pumping scheme.



Frequency dependence of the spectral broadening D of the probe wave in forward-pumped Raman amplifier. The best Lorentzian fir through the data points yields phonon lifetime in silica fibers: τ = 27 fs.



The sidebands experience higher gain than the central probe frequency due to the presence of MI.

Modified coupled evolution equations for propagation of two waves in a nonlinear medium with noninstantaneous response time τ:

$$\frac{\partial}{\partial z}A_1 + \frac{1}{v_{g1}}\frac{\partial}{\partial t}A_1 = -i\left(\frac{b_{21}}{2}\frac{\partial}{\partial t^2} - g_1|A_1|\right)A_1 - g_1 h(d)|A_2|\ A_1$$

$$\frac{\partial}{\partial z}A_2 + \frac{1}{v_{g2}}\frac{\partial}{\partial t}A_2 = -i\left(\frac{b_{22}}{2}\frac{\partial}{\partial t^2} - g_2 k(d)|A_1|\right)A_2 - g_2 h(d)|A_1|\ A_2$$

$$k(d) = (2-a) + \frac{a}{1+d^2t^2}$$ XPM coupling coefficient

$$h(d) = a\frac{dt}{1+d^2t^2}$$ Two-beam coupling gain

Conclusions:

We have analyzed the development of MI for two-beams in noninstantaneous nonlinear media. From the analysis of the experimental data we were able to extract an accurate value [τ = 27(1) fs] for the relaxation time of the Raman part of $\chi^{(3)}$ in silica. This type of experiment can be successfully used for the measurement of τ in other materials with anomalous dispersion for both the pump and the probe waves.