Contribution to the study of Raman effect in the evanescent field of a nanofiber immersed in a liquid

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Summary

Nanofibers enable exploring evanescent nonlinearities. In this context, we aim to characterize a nanofiber immersed in ethanol. A single mode fiber at 532 nm is used and the nanofiber diameter is increased. Designed tapers are adiabatic in ethanol helping to investigate the stimulated Raman effect.

Introduction

Nanofibers are tapered from silica fibers until reaching a diameter comparable or even smaller than the light wavelength. At such small diameters a strong confinement of light is obtained as well as an intense evanescent field useful for several applications such as sensors and nonlinear optics exploration. We recently demonstrated "evanescent" stimulated Raman scattering in a few cm length nanofibers pulled from a single mode fiber at 1550nm (ref. SMF28) and immersed in different liquids using sub-nanosecond pump pulses at 532 nm[1]. When the diameter is small (lower than 600nm), the component is very fragile. In this paper, we used a silica single mode fiber at both pump and Stokes wavelengths (ref. 460HP from Nufern) and we increased the nanofiber diameter to make the component more straightforward to manipulate. We present the theoretical design and the experimental performances of this nanofiber allowing the observation of the first Raman Stokes order of ethanol.

Discussion

The simulations are performed at a 532nm pump wavelength and the immersing Raman liquid is the ethanol. In order to estimate our nanofiber parameters (diameter and length), we plot the variation of modal Raman gain with the nanofiber radius as shown in Fig.1 [2]. In our previous work, the radius of the nanofiber immersed in ethanol was close to the optimum radius of 0.22 µm (M_1 in Fig.1). Such nanofibers were not easy to handle. We shift towards a bigger radius of 0.3 µm (M_2 in Fig.1) easier to manipulate. In order to estimate the suitable nanofiber length, we introduce the critical parameter $\gamma = g_{Rmodal} \times L \times P_{in}$ where g_{Rmodal} is the modal Raman gain; L is the nanofiber length and P_{in} is the input pump power for which the output pump power is equal to the Stokes output power. By assuming a sub-nanosecond-pulsed regime at 532 nm, this critical parameter is evaluated to be 20 [3]. We consider a peak power of 1 kW in order to stay below the silica damage threshold. Then, we compute L in order to reach $\gamma=20$. By choosing a radius of 0.3 µm, we have a modal Raman gain of 0.6 $m^{-1}W^{-1}$ and the nanofiber length has to be at least 35 mm which is feasible with our pulling process. Pulling the nanofiber from a single mode fiber at 532 nm allows us to avoid filtering the high order modes before immersing the nanofiber in the Raman liquid, which makes the experiment process simpler. Changing from SMF28 to HP460 needs to readapt the parameters of the pulling process. Particular care is paid on the adiabacity of tapers. Although being pulled in the air, our nanofiber should be adiabatic in ethanol. In Fig.2, we plot the limit between adiabatic

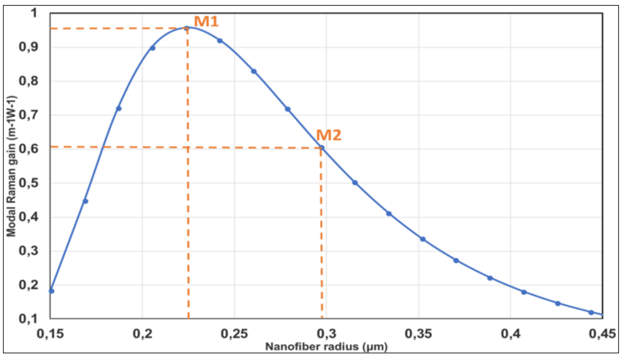

Fig. 1. Modal Raman gain as a function of nanofiber radius

and nonadiabatic zones as a function of the relative radius $\frac{\rho}{\rho 0}$ for different external medium indices at 532 nm where $\rho 0$ is the cladding radius equal to 62.5 μm. The initial core radius is 1.25 μm. The chosen criterion defining this limit is $\frac{1}{Z12} \geq \frac{1}{\rho}\frac{d\rho}{dz}$ [3] where $\frac{1}{\rho}\frac{d\rho}{dz}$ is the maximum allowed taper slope and Z_{12} is the beating length between LP_{01} and LP_{02} modes. We notice that the critical relative radius is around 0.4 for our fiber. When we increase the external medium index, the adiabacity limit is shifted up. Then, it is less constraining to be adiabatic in ethanol than in the air. This observation is confirmed experimentally. In fact, our designed taper is in the ethanol adiabatic zone. When we immerse our nanofiber in ethanol, we systematically notice an increase of the output signal power by about 7%. When the wavelength is higher, the adiabacity limit is right-shifted [4]. We checked that our tapers remain adiabatic at 630nm which is the first Raman Stokes order of ethanol. In order to investigate the stimulated Raman scattering over the fundamental mode, we pulled nanofiber with a radius of 0.3 μm, a length of 78 mm and taper lengths of 35 mm. The input and output unstreched parts of the fiber are, respectively about, 32 cm and 40 cm which limits the Raman effect in Silica. The light transmission of the whole component (unstreched parts, tapers, nanofiber) is 77% in the ethanol. The pump laser (from HORUS) has a maximum available peak pump power of 6.3 μJ, a pulse duration of 900 ps and a frequency repetition rate of 4.7 kHz. The laser damage threshold is experimentally estimated to be 160 J/ cm^2 for a nanofiber immersed in ethanol. We observe the threshold of the first Raman Stokes ethanol order at an incident pump energy E_{in}=0.27 μJ. In Fig.3, we report the spectrum at the output for two different pump incident energies (0.3 μJ and 0.6 μJ). Slightly above 0.6 μJ, the nanofiber was broken. To improve the performances, better adiabacity of tapers is in progress. Backward nonlinear effects limiting the forward beam are under study.

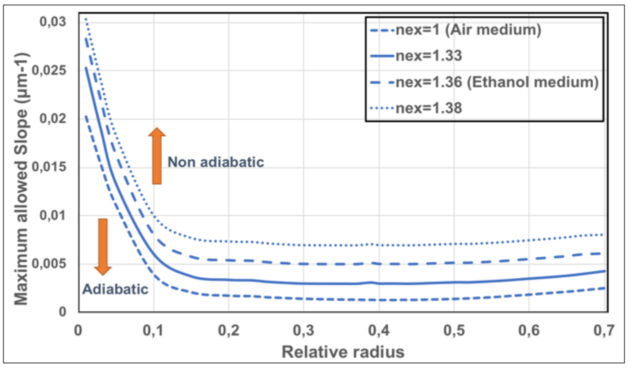

Fig. 2. Adiabacity limit for different external indices

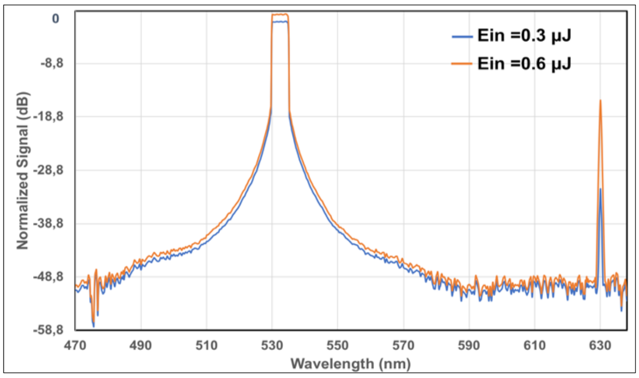

Fig. 3. First Raman Stokes observation

Conclusion

We present the observation of stimulated Raman scattering in the evanescent field of the nanofiber immersed in ethanol and pulled from a single mode fiber at 532 nm and having a radius higher than the optimized one which leads to a simplified experimental setup and an easily handling of the component. Studying Raman effect on the TM_{01} mode will be a next challenge opening the way to new opportunities in nonlinear optics, such as modal phase matching.

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