Optimal nanofiber dimensions for stimulated Raman scattering in the evanescent field

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Summary

In nanofibers, the guided mode presents a strong evanescent field. We investigate the Raman interaction between this field and a liquid surrounding the nanofiber. Our modeling demonstrates that the Raman conversion is obtained with nanofiber lengths an order of magnitude lower than for liquid core photonic crystal fibers.

Introduction

Optical nanofibers with a diameter smaller than the wavelength of the guided light exhibit a strong lateral confinement of the mode along with a pronounced evanescent field surrounding the fiber. These properties make optical nanofibers a unique tool for efficient and controlled coupling of light with matter on or near their surfaces [1,2]. A wide range of nanofiber applications is emerging in fields like, e.g., optical sensing, nanofiber-based evanescent wave spectroscopy and nonlinear optics. Hereafter, we investigate the use of this evanescent field to perform Raman conversion in the surrounding medium. We calculate the nanofibers parameters (length, radius) optimizing the stimulated Raman scattering in the surrounding liquids.

Modeling and discussion

We take the example of a nanofiber directly pulled from a standard SMF28 single mode fiber. Even though the nanofiber is originally pulled from a three-layer fiber, it is important to note that when it is pulled down to an external radius around 1 µm, such a nanofiber can be treated as a two-layer structure since the core diameter is about 14 times smaller than the cladding diameter. Neglecting the original core, considering the old cladding as the new core and the outside liquid as the second layer, we model the propagating fundamental HE_{11} mode using the vectorial approach [3]. We assume that the only nonlinear effect arising in this system is the Raman conversion in the surrounding liquid. Indeed we calculate that the Raman threshold of the silica fiber is much higher than the Raman threshold of the liquid we consider. We also check that Kerr effects (phase modulation instabilities, parametric generation,..) are unlikely to happen as the nanofiber immerged in the liquid operates in the normal dispersion regime. To model the Raman conversion in the liquid, we rely on the vectorial analysis [4]. In Fig. 1, we plot the modal Raman gain (g in $\mathrm{m^{-1}.W^{-1}}$) experienced by the guided mode on the first main Stokes line of the liquid versus the nanofiber radius. We simulate two pure liquids, ethanol and methanol, and a mixture of benzene and methanol. For this later, benzene is the Raman medium, methanol is just used to reduce the refractive index below the one of silica. The pump wavelength is 532 nm. For each liquid there is an optimum radius. For larger radii, the modal gain decreases because the evanescent field diseapears, the mode being more confined in the glass core. For radii smaller than the optimum, the evanescent field spreads over larger distances so that its amplitude diminishes: the modal gain decreases

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once again. One sees that, although the Raman coefficient of methanol, $g_R = 0.22\ 10^{-11}$ m/W, is smaller than for ethanol, $g_R = 0.31\ 10^{-11}$ m/W, the modal Raman gain experienced by the guided mode is about the same because the larger refractive index of ethanol makes the mode spread over a larger area. The Raman coefficient of the mixture is proportional to the fraction volume of benzene: $g_R = 5.0\ 10^{-11}$ m/W when used pure. Nevertheless the largest modal gains are also obtained for the lower refractive index mixture although the Raman coefficient of the mixture is lower. The optimum radii, around 220 nm for ethanol, are within reach of pulling systems.

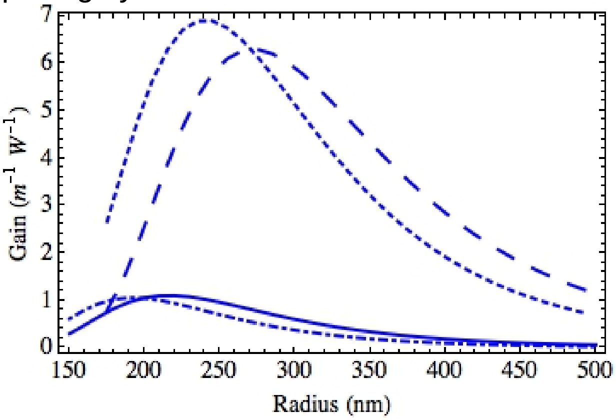

Fig.1: Raman gain experienced by the guided mode versus the nanofiber radius for various liquids: full line, ethanol (refractive index at 532 nm, *n* = 1.36); dot-dashed line, methanol (*n = 1.34*); short dashed, 50% benzene in volume with 50% methanol (*n* = 1.38); long dashed, 60% benzene and 40% methanol in volume (*n* = 1.40).

The nanofiber lengths required to achieve the Raman threshold condition are also realistic. We compute these lengths using the values for the modal gain g plotted in Fig.1 according to the formula $gPL \approx 16$ [5]. The pump power is equal to $P = 1$ kW, a value commonly provided by sub-ns Q-switch micro-lasers. At the optimum radius, for ethanol, we obtain $L \approx 15$ mm. This threshold length is about 10 times smaller in nanofibers than those reported in similar experiments in hollow core photonic crystal fibers, HC-PCF [6-8]. Furthermore, as deduced from Fig. 1, the accuracy on the fiber radius is not critical: a variation of this radius by 10% modifies the Raman gain by less than 10% in case of ethanol for instance.

Conclusions

Optimized parameters for the observation of stimulated Raman scattering are calculated. Compared with liquid filled HC-PCF, the same effects should be observed with nanofiber lengths ten times shorter. The characteristics of such fibers make them feasible [1].

Reference:

[1] L. Tong, J. Lou, E. Mazur, Opt. Express **12**, 1025 (2004).
[2] M.-A. Foster, A.-C. Turner, M. Lipson, A.-L. Gaeta, Opt. Express **16**, 1300 (2008).
[3] A.W.Snyder, J.Love “Optical Waveguide Theory”, Kluwer Academic Publshers, London (1983).
[4] M.-D. Turner, T.-M. Monro, S. Afshar V., Opt. Express **17**, 11565 (2009).
[5] G. Agrawal, “Stimulated Raman Scattering”, Chapt 8 in “Nonlinear Fiber Optics”, Academic Press London (2007).
[6] S. Yiou, P. Delaye, A. Rouvie, J. Chinaud, R. Frey, G. Roosen, P. Viale, S. Février, P. Roy, J.-L. Auguste, J.-M. Blondy, Opt. Express **13,** 4786 (2005).
[7] S. Lebrun, P. Delaye, R. Frey, G. Roosen, Opt. Lett. **32**, 337 (2007).
[8] S. Lebrun, C. Buy, P. Delaye, R. Frey, G. Pauliat, G. Roosen, Journal of Nonlinear Optical Physics & Materials **19**, 101 (2009).