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Operating range of efficient Raman converters based on nanofibers immersed in different liquids

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Abstract. We present the operating range of Raman wavelength converters based on silica nanofibers immersed in liquids for the design of all fibered wavelength converters. This range is bounded on the lower limit by the pump energy necessary to reach the Raman threshold and on the upper limit by the laser induced breakdown of the nanofiber. These breakdown energies are measured in the ns regime for different liquids (water, ethanol, isopropanol) and for air. We finally define guidelines that open the way to a new family of low-cost compact and efficient all-fibered Raman converters that can be directly inserted in optical fibered networks with very low losses.

1 Introduction

Optical tapered nanofibers are fabricated by pulling fibers until reaching diameters comparable or smaller than the light wavelength. Silica nanofibers are significantly exploited for a wide range of potential applications. Indeed, at such diameters, nanofibers exhibit a strong confinement of light which enables the generation of nonlinear effects [1]. Nanofibers can also exhibit an intense evanescent field which has been exploited for optical sensing, optical traps or spectroscopy. However, the experimental investigation of the optical nonlinearities in the evanescent field of the nanofiber remains limited to a few studies [2,3]. In this work, we focus on the Raman scattering in the evanescent field of a nanofiber immersed in a liquid. The Stokes photons are generated in the immersing liquid by the Raman scattering of the pump photons present in the evanescent field, then couple to a guided mode of the nanofiber and can be directly collected at the output of the un-tapered fiber.

The Raman conversion operating range of these wavelength converters is bounded on the lower limit by the pump energy necessary to reach the Raman threshold and on the upper limit y the laser induced breakdown of the nanofiber. To optimize the extracted Stokes energy, it is then necessary to decrease the Raman threshold energy and to increase the nanofiber breakdown energy. The Raman threshold energy can be estimated with a quite good accuracy by using a simple modelling based on modal Raman gain [2]. The breakdown threshold energy is much more difficult to predict, and experimental data have to be used. To increase this breakdown energy, one way is to increase the diameter of the nanofiber. However, higher diameters would increase the Raman threshold because the intensity of the evanescent field would be decreased. A compromise must be found in order to determine the nanofiber diameter enabling the extraction of the maximal output energy at the Stokes wavelength. In this work, we use ethanol as the Raman liquid. Laser breakdown energies with different liquids are also tested. We finally define guidelines that open the way to a new family of low-cost compact and efficient all-fibered Raman converters that can be directly inserted in optical fibered networks with very low losses.

2 Experimental setup

The nanofiber, attached to two un-tapered fibers through two sections called the tapers, is fabricated by following the "pull and brush" technique [2]. After the fabrication, the component is totally immersed in the Raman liquid. The radius of the nanofiber is determined by the modal Raman gain and its length is determined by the pump energy necessary to reach the Raman threshold. The tapers are designed to be adiabatic when immersed in the liquid. We focus our study on three different nanofiber radii: 220 nm, 300 nm and 350 nm. The length of all nanofibers is 8 cm. The transmission of the nanofibers with their tapers is routinely higher than 90%.

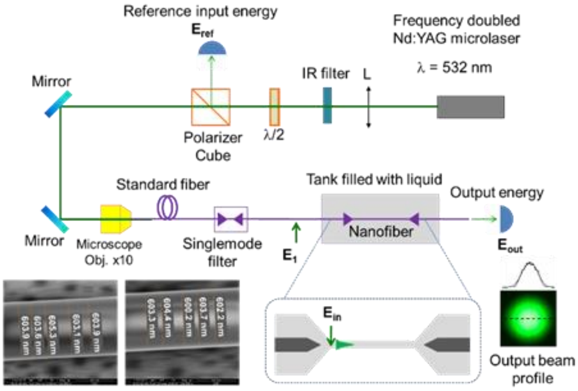

Fig. 1. Experimental setup. Bottom right: far-field picture of the output mode with cross section and Gaussian fit.

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Fig. 1 shows the experimental setup. The pump source is a frequency doubled pulsed pump laser emitting a beam at λp = 532 nm with a pulse duration of 900 ps (FWHM), a frequency rate repetition of 4.7 kHz and a maximum pump energy of 6.3 μJ. The pump beam is injected in the un-tapered input of the nanofiber and forward beams (pump at 532 nm and first Stokes order of ethanol at 630 nm) are sent after the un-tapered output to an optical spectrum analyzer.

3 Results

We present in Fig. 2 the experimental Raman threshold energies, incident nanofiber breakdown energies and maximum extracted Stokes energies for 20 samples of nanofibers having a radius of 300 nm. The conversion efficiency from the pump to the first Stokes order of ethanol is higher than 60%.

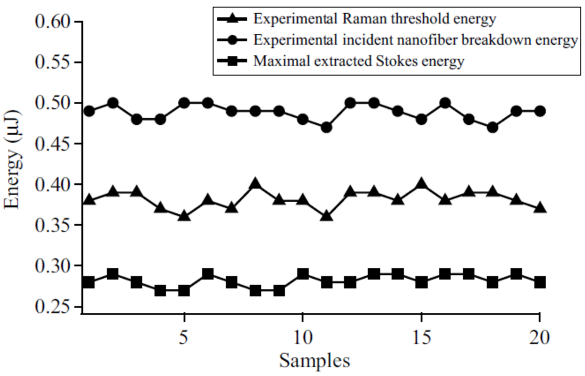

Fig. 2. Experimental Raman threshold and breakdown energies, extracted Stokes energy of 20 samples of nanofibers with a radius of 300 nm.

Fig. 3 shows the operating range, delimited by the Raman threshold and the laser breakdown energy of the nanofiber obtained with the three different radii studied. Each experimental point corresponds to the average of the results obtained with 20 nanofibers. These results illustrate the high reproducibility of the performances obtained.

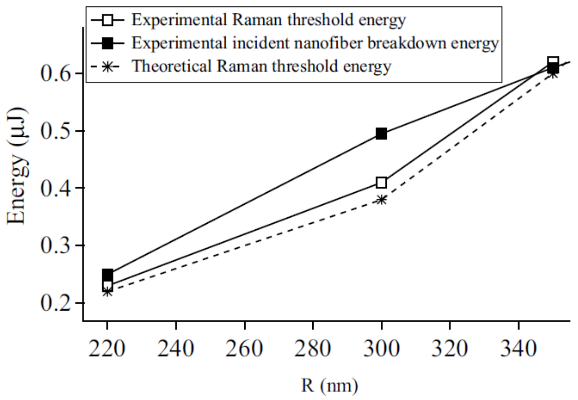

Fig. 3. Operating range of the Raman converters.

Since the nanofiber breakdown energy limits the performance of the Raman converters, we have experimentally studied this physical quantity for different liquids (water, ethanol, isopropanol) and different nanofiber radii [4]. Results are presented in Fig. 4. By knowing the pump energy at breakdown and by estimating the Raman threshold, it is possible to define the operating range of the converters for different immerging liquids and radii, by adapting, if necessary, the length of the nanofiber as we will show during the conference.

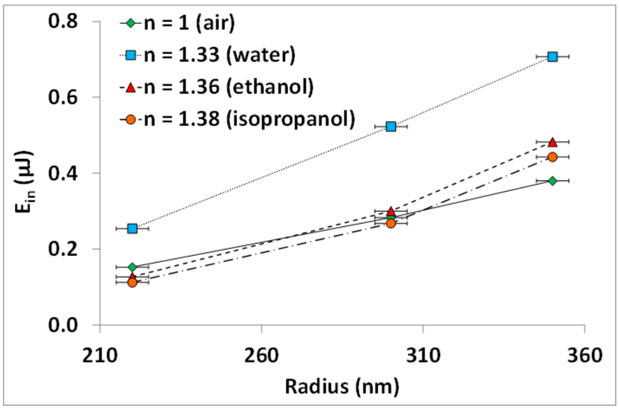

Fig. 4 Pump energy inside the nanofiber at breakdown for different radii and different liquids.

4 Conclusions and perspectives

We have demonstrated efficient and reproducible evanescent Raman converters in the nanosecond regime based on a silica nanofiber immersed in ethanol. We have defined an operating range which is a guideline for the conception of other evanescent Raman converters based on other liquids and/or fibers. Other perspectives are foreseen such as the deposition of nonlinear polymers on the nanofiber surface opening the way to a new family of robust all-fibered components that can be directly inserted in optical networks without additional losses.

References

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