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All-fiber Raman Probe using Higher Order Modes

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Abstract: We demonstrate the first all-fiber Raman probe utilizing higher order modes for the excitation. The spectrum of cyclohexane is measured using both the fundamental mode as well as in-fiber-generated Bessel-like modes.

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1. Introduction

The first all-fiber Raman probe was demonstrated by McCreery et al. [1] for *in vivo* measurements - seeking the potential of remote sensing. One challenge in utilizing an all-fiber probe is the diffraction of the beam emitted from the probe towards the sample. In-fiber-generated Bessel-like beams are shown to exhibit diffraction resistant behaviour as well as a very high intensity in the central peak [2], thus utilizing such modes for excitation in all-fiber Raman probe allows for deeper penetration into the sample. Bessel-like beams also show self-healing abilities which is very useful in turbid media [2].

In this paper we demonstrate the first all-fiber Raman probe using Bessel-like modes. We investigate two different higher order modes (HOMs), LP_{010} and LP_{012} , as well as the fundamental mode as excitation beam, we collect the Raman scattered signal in one 400 μm core multimode fiber. The HOMs are generated with an UV-written long period grating (LPG).

2. Experiments

A Raman spectroscopy measurement is conducted. The measurement setup is shown in Fig. 1. The sample used in this case is cyclohexane as it is a strong Raman scatterer.

Fig. 1. Raman spectroscopy setup. A laser emitting at 532 nm is focused into a single mode fiber (SMF) which is spliced to the airclad fiber with the UV-written LPG. The excitation and collection fiber (400 μm -core) is collected in a capillary tube with an inner diameter of 1 mm and thus constitutes the probe. The probe is emerged into the sample. The collection fiber (400 μm -core) is coupled into M25L01 (Thorlabs), where the numerical aperture matches the optics of the Andor Shamrock spectrometer.

The excitation fiber in the Raman probe is a double cladding structure, where the outer cladding is an airclad region. The germanium doped core has cutoff at 660 nm.

Emerging the fiber probe into the sample reduce the number of guided modes in the fiber as the capillary effect allows for the sample to fill the airclad and change the refractive index profile of the excitation fiber. Using a simple scalar mode solver shows cutoff of for a HOM well above LP_{012} .

A microscope image of the fiber end facet is seen in Fig. 2a. Mode images is recorded using a CCD camera. In Fig. 2b, the mode image of LP_{012} is depicted. The splicing from SMF to the airclad fiber is not yet fully optimized and we suspect that part of the mode coupling originates from the splicing. It is speculated, that core also guides LP_{11} , which

may result in further mode coupling. In Fig. 2c, the transmission spectrum of the LPG used for the excitation of LP_{012} is shown, the mode is generated with a conversion efficiency of 99%. The transmission spectrum is measured splicing SMF to both ends of the airclad fiber with the UV-written LPG and measuring the residual power in the fundamental mode.

Fig. 2. (a) Microscope image of the cleaved fiber end. The transverse width of the fiber is $120\ \mu\text{m}$. (b) Image of the LP_{012} mode at the fiber end facet. The mode generated in the airclad fiber with a UV-written LPG. (c) Transmission spectrum of the UV-written LPG, the spectrum shows a conversion efficiency 99% at 532 nm.

3. Results

To investigate the penetration of the modes into the sample, the propagation length as function of the mode order is found for the airclad fiber using Fourier propagation simulations, see Fig. 3a. For LP_{012} , the numerical simulation, see Fig. 3b is compared against measurements, see Fig. 3c. In terms of propagation length, the measurement and simulation show good agreement despite the impure mode image, see Fig. 2b. Both HOMs used, LP_{010} and LP_{012} ,

Fig. 3. (a) Propagation length as function of mode order simulated using Fourier propagation. (b) Intensity simulation of the propagation of the LP_{012} in air starting from the fiber end facet. (c) Measurement of the propagation of LP_{012} from the excitation fiber inserted in the fiber probe.

are shown to propagate a minimum of 6 times longer than the fundamental mode, see Fig. 3a. The choice of mode order for conducting the experiment is a balance of the propagation length and the self healing ability of the mode [2]. Lower order modes typically have poorer self healing abilities [2]. Simulations show that the different modes propagate different distances, see Fig. 3a. This may be utilized to create an all-fiber Raman probe with tunable depth of focus, by having a probe with an excitation fiber with multiple gratings exciting Bessel-like modes of different orders at slightly different wavelengths. Having a tunable source thus allows for changing the depth of focus [2]. This could be interesting when considering inhomogeneous samples. Another possibility for changing the region of illumination of the sample is to use a so-called bottle beam [3] or possibly the interference of two anti-symmetric HOMs, changing the Gouy phase allows for moving the high intensity region in the propagation direction away from the fiber.

The Raman response of cyclohexane is measured with three different probes, utilizing two HOMs, LP_{010} and LP_{012} and the fundamental mode for excitation. For all probes used, the same power is emitted from the probe, approximately 20 mW.

For Bessel beams, the power is equally distributed in the rings and the central peak [4]. The Raman response is expected mainly to be generated from the power in the central peak as the Raman response depends on the intensity. The Raman response is thus normalized to the number of rings plus one (for the central peak) in the HOM in question for comparison to the fundamental mode. The result is seen in Fig. 4, we see approximately the same response from LP_{01} and LP_{010} and a significant higher response for LP_{012} , there no evidence why that is the case. For all three probes, the distinct features of cyclohexane is measured.

Fig. 4. Raman response of cyclohexane, the Raman response of the is normalised to the number of rings in the mode plus one.

4. Conclusion

We demonstrate the first all-fiber Raman probe using Bessel-like modes, LP_{010} and LP_{012} , for the Raman excitation. The HOMs are excited in an airclad fiber. Simulations and experiment show a divergence resistant propagation distance LP_{012} of 260 μm , which is more than 6 times longer than the fundamental mode.

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