

Dependence of Raman scattering on the orbital angular momentum of light

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Raman scattering has found a variety of applications in areas such as amplification and spectroscopy [1,2], but it is also sometimes undesired, for instance, in power-scaling fiber lasers or in generating low-noise fiber-based quantum sources [3]. Controlling Raman scattering in fibers is thus important, but also a topic intensively studied, since its properties are generally well known. For instance, Raman gain is proportional to the nonlinear overlap integral $\int |E_p|^2 |E_s|^2 dA$, where E_p and E_s are the electric fields for pump and Stokes light, respectively [1] – a quantity that can be influenced by mode effective area. Also well-known is the fact that Raman gain is highest for co-polarized light [1]. Here, we show that orbital angular momentum (OAM) carried by light, which manifests as a helical phase $e^{iL\phi}$ of its field, where L is the topological charge, can also control Raman scattering. This seems counter-intuitive since the nonlinear overlap integral above indicates that Raman depends on intensity instead of electric field, so phase should not play a role.

We consider two pump cases – circularly and linearly polarized OAM beams. While the circularly polarized OAM beam behaves like any other fiber mode, a linearly polarized OAM beam is a superposition of left and right-handed circularly polarized σ^\pm fiber modes with the same L . Since these two modes are non-degenerate in effective index [4], we obtain a state that experiences circular birefringence Δn_{eff} , and hence optical activity (OA). Upon fiber-propagation, the mode remains linearly polarized, but rotates in polarization orientation [5].

In our experiment, the pump laser is a Q-switched Nd:YAG laser amplified with a 1.5-m long Yb-doped fiber. SLMs and polarization optics are used to sculpt and couple light into the desired OAM state of a ring-core fiber ($\Delta n = 0.035$, ring inner diameter = 21 μm , ring thickness = 5 μm) designed to stably propagate such modes [6]. Figure 1. (a) shows the measured near-field images for 8 different OAM modes – note that they have similar shapes and sizes, indicating that their nonlinear overlap integral for Raman scattering is similar. Figure 1. (b) shows spectra for two pumping cases of same input peak power (10 kW) – when the pump is in a circularly polarized OAM state ($L = 22, \sigma^+$) and when it is in the OA state ($L = 22, \hat{x}$). At one Stokes shift away from the pump (~1115 nm), it is clear to see that the Raman power of the OA state is 15 dB lower than that of the circularly polarized OAM input [7]. Spectral features close to the pump are four wave mixing peaks not described here – that they are comparable in both cases just confirms that the differing Raman strengths mentioned above are not artifacts from experimental variations. To study the origins of differing Raman gain responses just by changing polarization from circular to linear, we simulate this effect [8]. Figure 1. (c) shows that Raman gain for the OA state is maximized for a linearly polarized $L = 21$ mode – i.e. also an OA state but exactly one mode order lower than the pump. More generally, Raman gain appears to depend on mode order, which seems counter to Fig. 1. (a) that suggests Raman gain should be similar for all modes. This is resolved by considering the inherent polarization rotation of OA states with wavelength-dependent beat lengths, as shown in Fig. 1. (d). Polarization walk-off strongly diminishes Raman gain for a mode of the same L , and instead maximizes co-polarized interactions when the beat-lengths of the pump and Stokes modes match.

This demonstrates a dependence of Raman gain on the inherent chirality of optical fiber modes, and hence potentially provides an alternative means of tailoring Raman scattering in fibers.

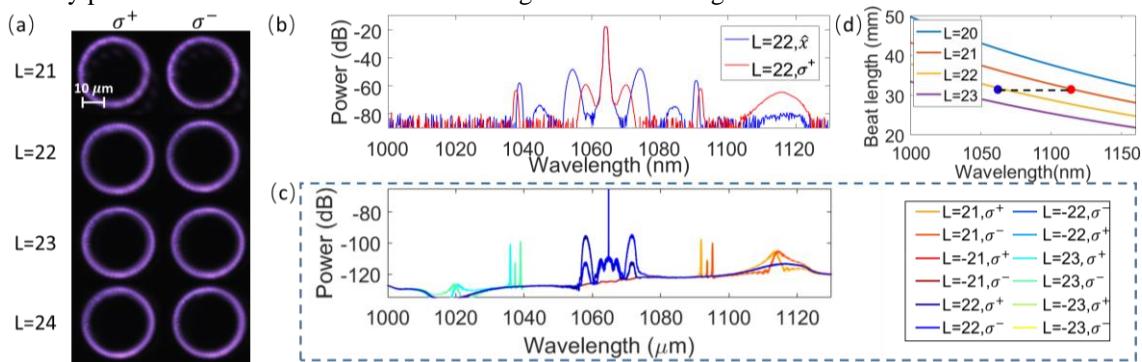


Fig. 1 (a) Near-field images of OAM modes considered (b) Experimental spectrum with pump in $L = 22$; σ^+ or \hat{x} state (c) Simulated spectra for pump in $L = 22$; \hat{x} (i.e. OA) state (d) OA polarization evolution beat lengths for $L=20-23$

References

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