# Dependence of Raman Scattering in a Few-Mode Fiber Within Small Detuning Range

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**Abstract:** We measure the intensity of small detuning Raman scattering in different spatial and polarization mode in a common circular core few-mode fiber, and show the existence of principle mode affect the dependence of Raman scattering. © 2022 The Author(s)

Recent research shows that the nonlinear effects in few-mode fibers (FMFs) have many applications. In particular, the sources of quantum states in higher order spatial and hybrid entanglement in frequency and transverse mode have already been realized by using the inter-modal four wave mixing in FMFs [1,2]. However, the Raman scattering (RS) which inevitably accompanies the four wave mixing in FMF degrades the performance of these quantum devices. To efficiently suppress the background noise originated from RS, it is necessary to investigate the mode dependence of the Raman scattering in FMF.

Our group recently studied spontaneous RS by using different kinds of 100-m-long FMFs when the detuning is greater than 6 THz [3]. The results indicated that the obvious dependence of RS on polarization and spatial mode can be observed in FMFs whose cross-section departs from cylindrical symmetry. But for the common FMF, which is circularly shaped with cylindrical symmetry and is widely used in mode-division multiplexing transmission systems, the dependence upon the polarization and spatial modes cannot be observed when higher order spatial mode is involved in the process of RS due to the random mode coupling. Considering the detuning of photon pairs generated via four wave mixing in FMF can be less than 6 THz [1,2], we investigate the RS at small detuning range as well. Here we report the experiment of measuring the intensity of RS with detuning in the range of 0.3-2.5 THz by pumping a 90-m-long common circular core few-mode fiber in different spatial mode. The results show that the dependence of intra modal RS at small detuning in higher order spatial mode is different from that at large detuning range due to the existence of principle mode [4].

Our experimental setup is shown in Fig.1. Spontaneous RS is produced by pumping a 90-meter-long circular core FMF, in which the spatial modes $LP_{01}$ and $LP_{11}$ are supported. The effective areas of the $\mathrm{LP}_{01}$ and $\mathrm{LP}_{11}$ modes are 24.1 and 66.7 $\mu\mathrm{m}^2$, leading to the nonlinear coefficients of about 4.2 and 1.5 $/(W \cdot km)$, respectively. The intensity of RS at frequency $\omega$ is related with the pump power $P_{p,n}$ and Raman gain $g_R$ through the relation

$$I_{R,m} \propto P_{p,n} n_T g_R L / A_{eff,nm} \tag{1}$$

where the subscripts $m$ and $n$ represent the spatial mode, $n_T$ denotes the number of optical phonons, $L$ is the length of FMF, $A_{eff,nm}$ is referred to as the effective interaction area between the pump in the n-th mode and RS wave in the m-th mode. For the RS in Stokes and anti-Stokes, the expression of $n_T$ is $n_T = n_{th} + 1$ and $n_T = n_{th}$, respectively, where $n_{th} = \frac{1}{e^{(\hbar\Omega/K_B T)}-1}$ with the detuning $\Omega$ determined by the difference between the central frequencies of RS and pump field is the Bose-factor. Considering the relation between the intensity of RS in Stokes and anti-Stokes sides in fiber has already been well characterized, here we only present the results of RS in Stokes side. To mitigate the influence of photons scattered from other nonlinear processes in FMF, the pump is obtained by passing the output of a mode-locked fiber laser through a filter $\mathrm{F}_{in}$ with 3 dB bandwidth of about 0.6 nm, and the central wavelength of $\mathrm{F}_{in}$ is 1545 nm.

The spatial mode of the linearly polarized pump can be varied by the phase plate (PP1). A beam splitter (BS) at the output of FMF is use to reflect residual pump and to monitor its mode by CCD. To measure the RS in different spatial and polarization mode, a mode de-multiplexer consisting of a quarter-wave plate (QWP), HWP2, PP2 and a piece of single mode fiber (SMF2) is placed at the transmission port of BS. To get rid of the influence of self-phase modulation effect, the pump power is relatively low. As a result, the intensity of spontaneous RS which is less than $10^{-2}$ photons/pulse is measured by a single photon detector (SPD). To reliably measure the RS at small detuning, a narrow band filter $\mathrm{F}_{out}$ is placed in front of the SPD to effectively isolate the pump. The central wavelength of $\mathrm{F}_{out}$ can be flexibility adjusted.

For each kind of pump configuration, we measure the co- and cross-polarized RS in $\mathrm{LP}_{01}$, $\mathrm{LP}_{11a}$ and $\mathrm{LP}_{11b}$ modes. $\mathrm{LP}_{01}$ mode is obtained by removing the phase plate PP2 and collecting the detected light into SMF2.

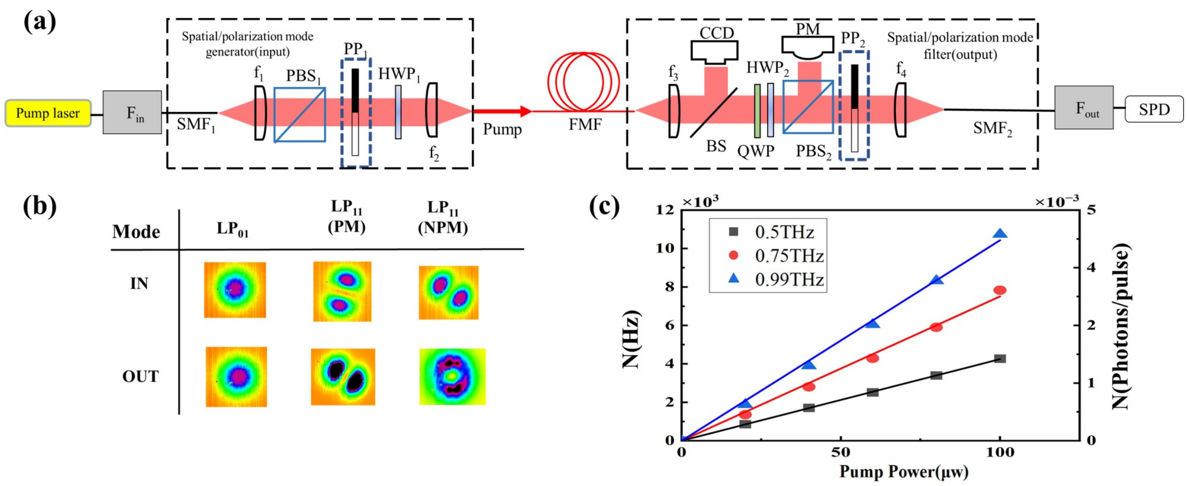


Fig. 1. (a) Experimental setup. (b) Intensity distribution at the input and output ports of FMF when the output of mode-locked laser is launched into the FMF along its principal mode (PM), non-principle mode (NPM)and $LP_{01}$ mode, respectively. (c) Counting rate of Raman scattering $N$ in the co-polarized $LP_{11a}$ mode at different detunings as a function of pump power for pump propagating along the principal mode of FMF. $N = s1P_p$ is shown to fit the experimental data (solid line).

$LP_{11a}$ and LP11bb modes are obtained by inserting the properly orientated PP2 and converting to $LP_{01}$ mode to match the mode of SMF2. Co- and cross-polarized RS are selected by adjusting HWP2 and QWP to maximize and minimize the intensity at the output of PBS2, respectively. For each set of data, the intensity of RS is corrected by the transmission efficiency from the output of FMF to the input of the SPD.

We first characterize the principle mode of the FMF and then measure RS when pump is respectively launched into the FMF along its principle mode and non-principle mode. In the process of characterizing the principle mode (PM), we temporally remove the narrow band filter $F_{in}$ to launch broadband optical field into the FMF. We then adjust the orientations of $PP_1$, $HWP_1$, and QWP and $HWP_2$ to minimize or maximize the power observed at the reflected port of $PBS_2$. In this case, the ratio between the maximized and minimized powers is about 10, indicating that the coupling between the spatial mode and polarization mode is negligibly small. Meanwhile, we monitor the spatial mode by CCD. As shown in Fig. 1(b), the patten of output mode is the same as that of input except a different orientation. Once the principal mode is found, we label the corresponding orientation angle of $PP_1$. When the orientation of $PP_1$ is rotated by another 45 degree, the pattern of output field becomes a mixing of $LP_{11a}$ and $LP_{11b}$ (see Fig. 1(b)) due to mode coupling. For the sake of convenience, we refer the latter case as non-principle mode(NPM).

When the pump propagates in FMF along the principal mode, we measurement intensity of RS as a function of detuning $\Omega$ in different mode. The mode $LP_{11a}$ is chosen to be the same as that of pump at output of FMF. Moreover, for RS in each spatial mode, we perform measurement when the selected mode is co- and cross-polarized with pump. Fig. 1(c) shows the counting rate ($N$) of RS in co-polarized $LP_{11a}$ mode, which is obtained by varying the pump power when the detuning is fixed at different values. We fit the measurement result with the linear function $N = s_1' P_p$ (solid line in Fig. 1(c)), where the fitting parameter $s_1'$, proportional to $n_T g_R$ at different detuning (see Eq. (1)), represents the strength of RS. The linear function well fits the data even if the detuning $\Omega$ is down to 0.3 THz, indicating the influence of the other nonlinear processes on the RS measurement is negligibly small. In the plot of the first row in Fig. 2, the solid circles represent $s_1$ (obtained by correcting $s_1'$ with transmission efficiency $\eta(\Omega)$) as a function of detuning $\Omega$. After adjusting the QWP and HWP2 to maximize the pump power measured at the reflected port of PBS2, we are able to select the RS which is cross-polarized with pump. The hollow circles in the first row of Fig. 2 are the results of RS in cross-polarized $LP_{11a}$ mode. One sees that the strength of co-polarized RS is much higher than that of the cross-polarized one. We then adjust the orientation of PP2 to select the RS in $LP_{11b}$ mode and measure RS in co- and cross-polarized mode. The results, represented by the triangles in the left column in Fig. 2, demonstrate that the strength of co-polarized case is slightly higher than that of cross-polarized case, but the difference between them is not as distinct as that in $LP_{11a}$ mode. Moreover, we find the strength of RS in $LP_{11b}$ mode are obviously lower than that in $LP_{11a}$ mode. The solid and hollow squares in the plot of the first row in Fig.2, which are almost overlapped, are the results of RS in co- and cross-polarized $LP_{01}$.

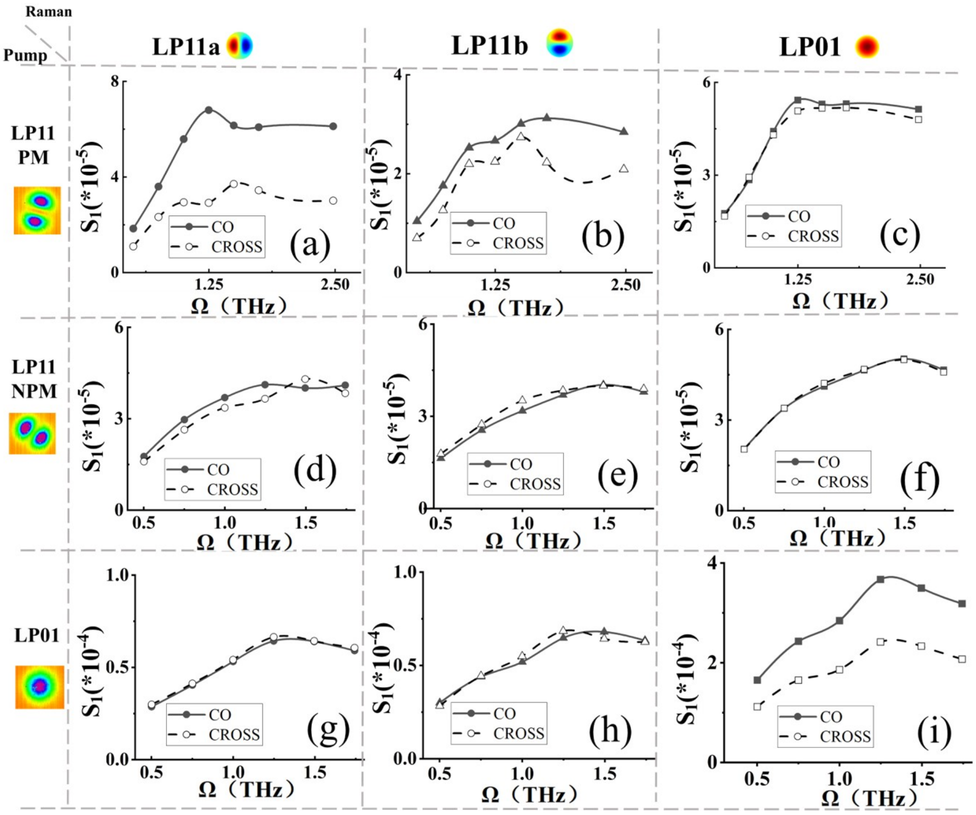


Fig. 2. Strength of Raman scattering in different mode for pump propagating along the principle mode (PM, first row), non-principle mode (NPM, second row ) and $LP_{01}$ mode (third row) in FMF.

The plots in the second row of Fig. 2 are obtained for the pump propagating in FMF along its non-principal mode.The results show that there is no observable difference between co- and cross-polarized mode for the RS in different spatial mode. Moreover, the difference of RS in $LP_{11a}$ and $LP_{11b}$ mode is not observable. We think the disappearance of dependence upon the polarization and spatial mode is because of the random mode coupling.

The plots in the third row of Fig.2 demonstrate the strength of RS in different mode when the pump is launched into the $LP_{01}$ mode of FMF. One sees that for RS in $LP_{01}$ mode, the strength of co-polarized RS is obviously higher than that of cross-polarized one, which is similar to the phenomenon of RS in single mode fiber; while for RS in higher order mode, the dependence is polarization and spatial mode is not observable.

The measurement results (see Fig. 2) show that the variation trends of RS in different modes are similar, but the strength of RS in different modes highly depends on the pump configuration. The strength of intra modal RS in $LP_{01}$ mode is about 2.5 times that in $LP_{11}$ mode. Moreover, for the intra modal RS in $LP_{11}$ mode, the co-polarized RS in $LP_{11a}$ mode obtained by launching the pump into the principle mode is the highest. We think the factors influencing the strength of RS are (i) nonlinear coefficient and (ii) mode coupling. The measurement of extending the detuning range of RS to 6 THz is underway. More results will be presented on the conference.

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## References


1. Cruz-Delgado, D., et al. ”Fiber-based photon-pair source capable of hybrid entanglement in frequency and transverse mode, controllably scalable to higher dimensions.” Scientific reports 6.1 (2016): 1-9.
2. Guo, Cheng, et al. ”Generation of telecom-band correlated photon pairs in different spatial modes using few-mode fibers.” Optics letters 44.2 (2019): 235-238.
3. Zhenzhen Zhang, Hongtao Cheng, Cheng Guo, Liang Cui, Yichi Zhang, Qi Mo, Huang Yu, Michael Vasilyev, Xiaoying Li“Investigation of Spontaneous Raman Scattering in Few-Mode Fibers: Dependence on Polarization and Spatial Modes,” Journal of Lightwave Technology **39**, 6281–6287 (2021).
4. Joel Carpenter, Benjamin J. Eggleton, Jochen Schröder“Observation of Eisenbud–Wigner–Smith states as principal modes in multimode fibre,” Nature Photonics **9**, 751–757 (2015).