Frequency tunable polarization and intermodal modulation instability in high birefringence holey fiber

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Abstract: - We present an experimental analysis of polarization and intermodal noise-seeded parametric amplification, in which dispersion is phase matched by group velocity mismatch between either polarization or spatial modes in birefringent holey fiber with elliptical core composed of a triple defect. By injecting quasi-CW intense linearly polarized pump pulses either parallel or at 45 degrees with respect to the fiber polarization axes, we observed the simultaneous generation of polarization or intermodal modulation instability sidebands. Furthermore, by shifting the pump wavelength from 532 to 625 nm, we observed a shift of polarization sidebands from 3 to 8 THz, whereas intermodal sidebands shifted from 33 to 63 THz. These observations are in excellent agreement with the experimental characterization and theoretical estimates of phase and group velocities for the respective fiber modes.

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1. Introduction

Photonic crystal fibers (PCFs) provide a unique testbed for exploring complex nonlinear optical processes such as transient Raman scattering [1] and polarization or cross-phase vector modulational instabilities [2-5]. Indeed, nonlinear PCFs exhibit tight confinement of light owing to their small modal cross sections, whereas engineering of the hole and pitch structures enables tailoring of the frequency dependence of modal group velocities and group velocity dispersions [6]. Based on these properties, it is expected that PCFs will represent a basic component in nonlinear optical devices such as parametric frequency converters [7] and oscillators [8]. It has been recently shown that the strong frequency-dependence of the phase matching condition in PCFs may lead to widely tunable sidebands by means of a relatively small shift of the pump from the zero dispersion wavelength [9].

One of the most striking manifestations of nonlinear light manipulation in PCFs is supercontinuum (SC) light generation [10]. Phase matched four-photon parametric mixing [11-12] associated with Raman scattering is the basic mechanism for such spectral broadening, which can be observed even in the normal group velocity dispersion (GVD) regime. Several experiments have demonstrated that the early stage of SC generation is strongly dependent upon the state of polarization of the pumping pulses [13-16]. It is therefore...
of particular interest to explore the polarization dynamics of parametric scattering in the holey fibers [17].

In this paper, we present a detailed discussion of the first experimental demonstration of frequency-tunable (in the range of 3-8 THz) vector or cross-phase modulation instability in an optical fiber [18]. Moreover, we show that intermodal MI enables for simultaneous generation of high frequency (in the range of 33-63 THz) tunable sidebands in a PCF, when the pump wavelength is shifted from 532 to 625 nm. In order to achieve sideband shifting, we exploited the strong frequency dependence of polarization and intermodal group velocity mismatch (GVM) in the birefringent PCF with triple defect in the hexagonal lattice [19].

2. Birefringent PCF with elliptical core

The frequency detuning of polarization sidebands may be controlled by varying the group birefringence $G(\lambda)=B-\lambda dB/d\lambda$ (or GVM between orthogonally polarized modes), where B is phase modal birefringence defined as $B(\lambda)=\lambda(\beta_x-\beta_y)/2\pi$. The birefringent holey fiber under test was recently manufactured by the Laboratory of Optical Fiber Technology, UMCS in Lublin, Poland [19]. A SEM image of the central part of the fiber cross section is shown in Fig. 1(a). Its special feature is a highly elliptical core formed by a triple defect in the hexagonal lattice. Similarly to conventional optical fibers, high ellipticity of the core induces form birefringence, whereas the strong confinement of the mode field leads to enhancement of third-order nonlinear effects.

To model the dispersion properties of this fiber, we used a fully vectorial mode solver based on hybrid edge-nodal finite-element method (FEM) with a perfectly matched layer (PML). Due to technological problems mainly associated with the very small diameter of the holes, the fiber structure is not uniform. From the SEM image, we determined the pitch length $\Lambda$ from an average over the first two rings of holes, which is $\Lambda=1.09\pm0.05$ $\mu$m. It was much more difficult to determine in a reliable way the holes’ dimensions, because they are different in diameter and some of them have elliptical shapes. To account for this problem, we used especially developed software, equipped with filtering and discrimination features, that allowed us to reproduce the real fiber geometry from its SEM image and finally to generate the mesh for FEM calculations that reflects the real shape and location of each hole.

The results of calculations of phase (B) and group (G) birefringence for both the fundamental mode (LP\textsubscript{01}) and the first order mode (LP\textsubscript{11\text{even}}) are displayed in Fig. 1. To verify the modeling results, we also measured B and G for both spatial modes. The spectral dependence of the phase birefringence B was determined by the lateral force method, using several laser diodes operating in the range 530-830 nm [20]. The group modal birefringence G was measured with the scanning wavelength method. In this experiment, we used a broad band superluminescent diode with its central wavelength equal to 830 nm and an optical spectrum analyzer in order to register the interference effect [19]. The corresponding experimental values indicated by dots in Fig. 1 are in very good agreement with the modeling results, which confirms the validity of our numerical approach.

In Fig. 2, we also present the calculated spectral dependence of the GVD for the LP\textsubscript{01} and LP\textsubscript{11\text{even}} modes of both polarizations. These results show that in the analyzed wavelength range the GVD is positive (normal GVD regime) for both spatial modes. The limited spectral range of the calculations of the GVD for LP\textsubscript{11\text{even}} is related to the cut-off effect that arises for this mode at 850 nm.

3. Tunable vector modulation instability

In the MI experiments, quasi-CW pumping conditions were achieved by using nanosecond pulses from a frequency-doubled Nd:Yag laser operating at the repetition rate of 25 Hz (see Fig. 3). By using ns pulses, we could ensure full temporal overlap between the pump and the sidebands throughout the whole 5 m long sample of the PCF. The peak power of the pulses in the fiber was kept constant and equal to 30-40 W. We obtained additional pump wavelengths (574.5 nm and 625 nm) by frequency shifting the intense beam at 532 nm inside a CO\textsubscript{2} cell.
Frequency shifts resulted from self-stimulated Raman effect taking place in carbon dioxide, which was confined in a multiple-pass chamber. At the cell output, a direct vision prism (DVP) followed by a diaphragm was used to select the desired pump wavelength. By means of this setup, we could modify both the input power and the polarization state of the

![SEM image of the birefringent holey fiber with triple defect](image)

Fig. 1. SEM image of the birefringent holey fiber with triple defect (a), calculated and measured (dots) spectral dependence of phase (B) and group (G) modal birefringence for LP_{01} and LP_{11}^{even} modes (b-c).

![Graph of B vs. \( \lambda \)]

![Graph of G vs. \( \lambda \)]

Fig. 2. Group velocity dispersion (GVD) against wavelength calculated for LP_{01} and LP_{11}^{even} modes.
input beams by using a triplet composed by two half-wave plates and a polarizer set between them. To reduce astigmatism and obtain efficient coupling between the incident beam and the PCF modes, we used a 20 x microscope objective (MO). After propagation through the fiber, light was first collimated by means of a second microscope objective and then launched into a spectrometer.

In order to observe vector MI (VMI) in the high birefringence fiber under test, we launched the 40 W peak power pump beam linearly polarized and aligned at 45° with respect to the fiber polarization axes. Under these conditions, orthogonally polarized sidebands are generated owing to the compensation of GVD mismatch by means of GVM or G [17]. The black solid curves in Fig. 4 show the spectra (without polarization discrimination) with a pump wavelength of 532 nm and 625 nm, respectively. In Fig. 4, we compare the experimental spectra with computation results of beam propagation with quantum noise coupled to the CW pump beam: here blue and red spectra are associated respectively with x- and y-polarized components of the output field.

In our simulations, we used the linear birefringence and the modal nonlinear coefficients as estimated from the propagation constants and transverse field profiles calculated from the linear mode solver. Orthogonal polarization of VMI sidebands was confirmed by the experiments. The results of Fig. 4 show an impressive agreement between theory and experiments. The observed polarization sideband detuning grew from 2.6 THz with a pump at 532 nm, up to 4.14 THz with a pump at 574 nm (not shown here) and 8.5 THz with a pump wavelength of 625 nm.

In Fig. 4, we show calculated (upper curves) and measured polarization sidebands for two pump wavelengths equal respectively to 532 nm (left) and 625 nm (right).

Fig. 3. Experimental set-up: CO₂ - MPC: CO₂ Multiple-Pass Cell, DVP: Direct Vision Prism, λ/2: half-wave plate, POL: Glan Polarizer, MO: Microscope Objective, HB-PCF: High-Birefringence Holey Fiber.

Fig. 4. Calculated (upper curves) and measured polarization sidebands for two pump wavelengths equal respectively to 532 nm (left) and 625 nm (right).
4. Tunable intermodal modulation instability (IMI)

As shown in the bottom curve of Fig. 5, in addition to the low-frequency VMI sidebands, whenever the pump polarization was oriented at 45° with respect to the polarization axes of the PCF, we also observed two narrow parametric sidebands at a relatively high detuning from the pump. We verified that these sidebands are polarized in parallel to the pump. The numerical calculation of modal GVD and higher order dispersion permits to exclude fourth-order dispersion [6] as the phase matching mechanism for these sidebands. On the other hand, the modeling results presented in the upper curves of Fig. 5 show that the position of the sidebands with large frequency detuning agrees very well with the phase matching condition of parametric four wave mixing involving group velocity matching (GVM) between the fundamental LP$_{01}$ and the LP$_{11}^{\text{even}}$ mode with parallel polarizations. The phenomenon of MI induced by group-velocity matching of different guided modes was earlier studied in conventional multimode fiber by Stolen in [21] and more recently in [12,22]. The simulation results shown in Fig. 5 involved four coupled nonlinear Schrödinger equations for the LP$_{01}$ and LP$_{11}^{\text{even}}$ modes in each polarization. In the numerical fit, we neglected linear mode coupling but we kept cross-phase modulation (XPM) among either orthogonal mode components or parallel components of different spatial modes. Linear modal analysis provides overlap integrals and XPM coefficients. In Fig. 5, peaks C-D are due to VMI, whereas we may identify peaks A-F and B-E as due to GVM of LP modes with parallel polarization.

The observed ratio between the detuning of low and high frequency sidebands in Fig. 5 equals the ratio between group modal birefringence of the LP$_{01}$ mode ($G_{01} = N_{01x} - N_{01y}$) and the difference in group effective indices for LP$_{01}$ and LP$_{11}^{\text{even}}$ modes ($N_{01}-N_{11}^{\text{even}}$) of the same polarization. Figure 6 shows numerically calculated and measured (dots) values of $N_{01}-N_{11}^{\text{even}}$ for the x- and y-polarized modes. One should note a very good agreement between measured and theoretical values of $N_{01}-N_{11}^{\text{even}}$. In the simulations, the 40 W input pump pulses were divided as follows: we coupled 15 W of pump power into each of the LP$_{01}$ modes, and 5 W into each of the LP$_{11}^{\text{even}}$ modes.

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**Fig. 5.** Theory (upper curves) and experiment with pump at 532 nm: C and D are peaks from VMI, whereas peaks A, B, E, and F result from IMI.
As shown by the spectra in Fig. 7, GVM of intermodal modulation instability or IMI was observed whenever the pump polarization was rotated by 45° in order to be aligned in parallel to either the x- or y-axis of the PCF. In Fig. 7 we show the experimental spectra (green curves) and the calculated spectra for the LP$_{01}$ modes (top Fig. 7) and LP$_{11}$ even modes (middle Fig. 7) with x- (blue curves) and y-polarizations (red curves), and with a pump aligned in parallel to either the x- (left Fig.7) or the y-axis (right Fig. 7) of the PCF. In this experiment, the pump wavelength was equal to 532 nm, and the peak power of the pump pulses was equal to 30 W. Once again the sideband detuning agrees well with the theoretical estimates, in which the beam propagation simulations included the GVM and the XPM coefficients as obtained from the vector mode solver. In the simulations shown in Fig. 7, we coupled 20 W of pump power into the LP$_{01x}$ or LP$_{01y}$ mode, and 10 W into the LP$_{11x}$ even or LP$_{11y}$ even mode, respectively. The sideband detuning observed in Fig. 7 is equal to 34.7 THz for the x-polarized pump and 33.2 THz for the y-polarized pump, respectively.

In order to confirm the strong wavelength dependence of sideband detuning, we carried out the same experiment with the pump wavelength increased to 574 nm and 625 nm. The experimental results at 574 nm show a corresponding increase of the IMI sideband detuning to 48.3 THz and 45.9 THz with the pump polarization oriented respectively along x- or y-axis of the fiber. Whereas the experimental results at 625 nm show that IMI sideband detuning grows up to 63 THz with the pump polarization oriented along one of the fiber axis. Sideband frequencies can be expressed in a simple form by means of the phase matching condition of a specific four-photon parametric process. Such phase matching condition reduces to a particularly simple expression if we may neglect pump induced nonlinear contributions to the
wave vector mismatch, and we may neglect higher order dispersion terms besides GVD. Indeed, in our experiments VMI and IMI are induced by analogous pump-divided scattering processes. In the case of VMI, phase matching leads to the sideband frequency detuning

$$f_{\text{VMI}} = \frac{1}{\pi} \frac{\beta_y - \beta_x}{\beta_y + \beta_x}$$

Here $\beta_{x,y}, \beta^*_{x,y}$ are the first and second order $\omega$-derivative of the propagation constant of the fundamental mode with a linear polarization on the x or y fiber axis. For IMI, subscripts x and y in Eq. (1) should be replaced by 01 and 11 for a fixed polarization axis (x or y).

A summary of our modulation instability experiments is provided by Fig. 8, where we show the sideband positions as a function of the pump wavelength, which is indicated by a red curve. In Fig.8, triangles and dots represent respectively IMI and VMI, whereas the dashed blue curves indicate the linear phase matching condition for VMI (Eq. (1)), and black dashed and grey curves display the same phase matching condition for IMI on each polarization axis. The agreement between Eq. (1) and the experimental results may be affected by unavoidable fluctuations of the actual values of the GVMs of the PCF. Shaded regions (soft blue) enclosing the IMI phase matching curves of Fig. 8 indicate error bands for the sideband frequency offset corresponding to a ±10% variation of the difference of group effective indexes of the LP01 and LP11\text{even} modes ($N_{01} - N_{11}\text{even}$) with respect to the results of Fig. 6.

5. Conclusion

In this work, we report the first experimental investigations of the frequency tuning properties of VMI in a PCF, and demonstrate a sideband shift from 2.6 to 8.5 THz by up-shifting the pump wavelength by 93 nm, that is from 532 to 625 nm. Moreover, we observed the simultaneous generation of high frequency sidebands owing to modal GVM matching of the GVD. The position of these IMI sidebands shifted from 33 to 63 THz in response to increase of the pump wavelength from 532 to 625 nm. These observations show that the strong frequency-dependent linear propagation characteristics of guided modes in the holey fibers may be used to obtain a flexible source of parametric gain and broadly tunable oscillation.

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