Fast-light-assisted four-wave mixing in the photonic bandgap

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In this Letter, the enhanced four-wave mixing (FWM) in the photonic bandgap of fiber Bragg grating (FBG) has been achieved with an extra phase introduced by fast-light effect in the bandgap. The experiment for phase-matched FWM generation in the bandgap in a special-designed FBG was carried out, as well as simulations. The enhanced energy conversion with such a FWM in the bandgap has been demonstrated but the transmissivity has not. The experimental results show agreement with the simulations. © 2015 Optical Society of America

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Photonic bandgap can be created in various kinds of periodic photonic structures in which the energy cannot transmit through the medium [1]. Since the forward and backward waves are coupled in the bandgap, a standing wave is formed, and thus, the net transmission of energy is prohibited. Consequently, any kinds of effects related with light propagation, including nonlinear effects such as four-wave mixing (FWM), are traditionally regarded as impossible in the photonic forbidden band. Usually, to convert energy out of the bandgap, the transmissivity in the bandgap should be enhanced. Simulations as well as experiments for phase-matched FWM generation in a special-designed FBG were carried out. The enhanced FWM in the bandgap has been observed without the increase of transmissivity [21], the optical phase is supposed to vary rapidly along propagation, and thus this phase can be manipulated. As an application, the sensitivity enhancement of interferometer with a factor of 100 was reported [2].

On the other hand, FWM is a phase-dependent nonlinear effect without threshold effect [10], so it can be enhanced in zero-dispersion media [11] or through introducing an extra phase to satisfy the phase-matching condition. Recently, controlling the conversion efficiency via stimulated Brillouin scattering slow light [12], and FWM in photonic crystal waveguide [13,14], or via electromagnetically induced transparency slow light [15] have been reported. However, it is usually the slow-light effect that used to enhance nonlinear effect owing to the increase of power density [16], but not the fast light.

In our work, the fast light effect in the photonic bandgap of FBG is used to control the optical phase. Simulations as well as experiments for phase-matched FWM generation in a specially-designed FBG were carried out. The enhanced FWM in the bandgap has been observed without the increase of transmissivity. This gives the confirmation of FWM generation in the photonic bandgap by fast light rather than slow light. With a moderate low power (~200 mW), our scheme involves little influence from unnecessary nonlinear effects.

It is well known that the FBG is a key component in many fields owing to its excellent behavior as optical filters [17]. Also, it is a device of 1D photonic bandgap. Due to strong dispersion both in reflection and transmission around the bandgap [1,18], the optical phase is supposed to vary rapidly [19] and thus causes a considerable group delay or advancement. The coupled-mode theory has been used to explain the transmission characteristic of a uniform FBG [19,20]. Since the group delay in transmission equals to the one in reflection [21], the group delay transmitted through a FBG can be expressed as [22].
\[ \tau(\lambda) = \tau(\lambda) = \frac{\lambda^2}{2\pi c} \frac{d\varphi}{d\lambda}. \]  

where \( \lambda \) is the wavelength, \( c \) is the light speed in vacuum, and the transmission phase \( \varphi \) is

\[ \varphi = -\arctan \left( \sqrt{\frac{\kappa^2 - \sigma^2}{\sigma}} \coth \left( \sqrt{\frac{\kappa^2 - \sigma^2}{\sigma}} L \right) \right), \]

where \( L \) is the FBG length, \( \kappa \) is the coupling coefficient, and \( \sigma \) is the detuning.

Because the same phase shifts are introduced in both propagation directions, forward and backward waves remain coupled with each other [20]. Thus, even if the slow-/fast-light effect is considered, the transmission in the photonic bandgap is prohibited.

Figure 1 shows the measured features of the apodized FBG used in our experiment, which is fabricated on a standard single-mode fiber (SMF). Its length is 10 cm, and the Bragg wavelength is 1550.186 nm with a 3-dB bandwidth of 0.158 nm. The optical phase as well as the group delay was also derived. The delay of 68.48 ps at left, 62.75 ps at right band edge, and an advancement of 68.71 ps in the bandgap were measured. Figure 1(b) shows the discontinuity of optical transmission phase that result from the slow-/fast-light effect near/in the bandgap. Thus, with the variation on the group velocity, the propagation coefficient and the optical phase can be manipulated.

Without considering other nonlinear effects under low power level, a degenerated FWM is controlled by the phase-matching condition as [11].

\[ \Delta \beta = 2\beta_p - \beta_s - \beta_i, \]

where \( \beta_{p,s,i} \) are the propagation coefficients of the pump, signal, idler wave, respectively. With the manipulation of the propagation coefficient via slow-/fast-light effect, the phase-matching condition \( \Delta \beta = 0 \) can be achieved. The calculation shows, considering the extra optical phase in the bandgap [23], the dispersion of 3919.71 ps/nm with a corresponding advancement of ~66.62 ps can compensate the phase-mismatch of FWM with ~0.5 nm spacing in SMF.

To verify the above analysis, simulations of the FWM in such a FBG were conducted by using OptiSystem. In the simulations, the coupled-mode equation [19] is solved to calculate the transmission and reflection spectra of FBG, and the nonlinear Schrödinger equation [24] is applied to simulate FWM process. The FBG parameters for simulations are the same as the measured results in Fig. 1. The powers of two input lights were set at 200 mW. One input light was fixed at the wavelength of 1549.7 nm, while the other input light was fine tuned from 1550.02 to 1550.35 nm for covering the photonic bandgap of the FBG. Figure 2 shows the simulation results of FWM without considering the fast-light effect, in which the variation of optical phase around the bandgap was not included. The physical meaning is that the FWM is considered as a phase-mismatch process without compensation by the slow-/fast-light effect. With the pump wave approaching the bandgap, only part of the energy was involved in the FWM process and accordingly, idler power together with pump power decreased dramatically. Thus, as one input light is located in the bandgap, idler waves in both sides plunged into noise level. In contrast, when the fast-light effect in the bandgap was taken into account, a different tendency was demonstrated. Specifically, the maximum power change of 7.14 dB on the left side and 12.32 dB on the right side was well illustrated in Fig. 3. Owing to the slow-light effect at the band edges [19], obvious drop of idler power at 1549.14 and 1549.28 nm on the left and 1550.47 and 1550.88 nm on the right side were shown. Meanwhile, an enhancement of idler power was
observed due to phase-matching in FWM while the pump located in the bandgap, where the fast-light effect took place. Similar to Figs. 1(b) and 2(b), the superposed spectra in Fig. 3(b) obviously illustrates that the transmissivity of the input light passing through the bandgap is not enhanced, even if the fast-light effect is considered. Although forward wave do not almost transmit through the FBG \[25\], energy conversion is still achieved with the phase-matched FWM under the assist of the fast-light effect. Therefore, there is no doubt that the prohibited forward wave in the bandgap is involved in the FWM process.

According to the above derivation, the dispersion coefficient, which manipulates the slow-/fast-light effect, is a key factor to generate the FWM in the bandgap. The group delay can be calculated based on \(\kappa\) according to Eqs. (2) and (3), and thus the FBG can be designed for compensating the phase-mismatch in the FWM generation in SMFs. In Fig. 4, the advancement in the photonic bandgap shows a monotonous rising tendency with the product of \(\kappa L\) \[20\], which represents the dispersion introduced in the bandgap. Since the transmissivity drops as the rise of \(\kappa L\), the idler powers decrease in both sides with the increase of \(\kappa L\), no matter whether the fast-light effect is considered. However, with \(\kappa L\) increasing, the idler power difference between with and without fast-light effect becomes larger. However, a lower idler power (\(\sim -55\) dBm) without considering fast-light effect could not be observed owing to the background noise in FWM process. Thus, a limited idler power difference of 20 dB between two cases was illustrated.

Figure 5 shows the experiment scheme, in which two input lights with different wavelengths were emitted by two tunable laser sources (TLSs). Two erbium-doped fiber amplifiers (EDFAs) amplified the pump and signal lights for generating FWM. The polarization-independent isolator protected EDFAs from the light reflected by FBG. The abovementioned FBG provided the input light an appreciable delay at its band edge as well as advancement in the photonic bandgap. Through 1% output-port of a 99:1 optical coupler (OC), the FWM spectra were monitored by an optical spectrum analyzer (OSA).

In order to demonstrate how the slow-/fast-light effect influences the FWM efficiency, an experiment was carried out. One input light was set at the wavelength of 1549.7 nm, which was far from the bandgap of FBG, the other input light was fine tuned from 1550.04 to 1550.32 nm, which sweeps the whole bandgap region of the FBG. The lights output from OC1 were monitored by an OSA to ensure that two input waves were amplified to a specific power. Their power fluctuations during the experiment can be ignorable. Through monitoring the spectrum output from OC2, the power changes of idler waves during the sweeping of the input wave were observed. In the experiment, the power of both input lights was fixed at 200 mW. The experiment demonstrated that the transmissivity of the light passing through the bandgap is not enhanced. The transmission loss is same at the one in Fig. 1(b).

As shown in Fig. 6, there exist several peaks and hollows in either side of idler wave spectrum. When the pump light aimed
at the band edge of FBG at 1550.11 nm, which experienced a group delay of 68.48 ps (slow-light effect), thus idler powers in both sides suffered a decrease, i.e., 1.826 dB on shorter and 1.204 dB on longer wavelength side. As the pump wave tuned to the band edge of 1550.26 nm, experienced a delay of 62.75 ps (slow-light effect), and the idler powers in both sides also dropped, by 2.023 dB in shorter wavelength and 1.507 dB in longer part. However, while the pump light was fixed in the bandgap and got an advancement of 68.71 ps, and the fast-light effect on the input pump light compensated the phase-mismatch of FWM generation in the SMF. The idlers of both left and right sides generated by FWM in the bandgap are greatly enhanced. The idler powers can even exceed the one generated outside the bandgap, although the forward transmission of the pump light is still forbidden. However, due to phase-mismatch and short fiber length [10], FWM could not be observed with the substitution of a standard SMF with the same length to the FBG in this experiment. The experimental result showed a good agreement with the simulation.

In conclusion, we have proposed and demonstrated the FWM generation in the photonic bandgap. The enhanced energy conversion to the channels out of the bandgap was observed in the phase-matched FWM by introducing extra phase shift via the fast-light effect. With the assistance of such an extra phase, not only FWM but also many other nonlinear effects in the photonic bandgap can be expected. Such a way may be used to detect optical signals that usually filtered out by a photonic bandgap filter.

Fig. 6. Experimental results of FWM generated in the bandgap. (a) The 3D superposition of FWM spectra with varying pump wavelengths, showing the input light sweeping process. (b), (c) Illustrate the envelopes of the left and right generated idler lights with the input pump light sweeping process.

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