Phase-matched four-wave-mixing by the fast light effect in fiber Bragg gratings

CONFERENCE PAPER · JULY 2015

7 AUTHORS, INCLUDING:

Liang Zhang
Shanghai Jiao Tong University
23 PUBLICATIONS  127 CITATIONS

Le He
Shanghai Jiao Tong University
3 PUBLICATIONS  3 CITATIONS

Jinmei Liu
East China Normal University
22 PUBLICATIONS  137 CITATIONS

Li Zhan
Shanghai Jiao Tong University
143 PUBLICATIONS  1,286 CITATIONS

All in-text references underlined in blue are linked to publications on ResearchGate, letting you access and read them immediately.

Available from: Cheng Feng
Retrieved on: 22 December 2015
PHASE-MATCHED FOUR-WAVE MIXING BY THE FAST LIGHT EFFECT IN FIBER BRAGG GRATINGS

Cheng Feng, Liang Zhang, Hao Luo, Caixia Gao, Le He, Jinmei Liu, Li Zhan,

Department of Physics and Astronomy, Key Laboratory for Laser Plasmas (Ministry of Education), State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai, 200240, China

Department of Physics, East China Normal University, Shanghai, 200240, China

*Corresponding author: lizhan@sjtu.edu.cn

ABSTRACT

We demonstrate the phase-matched four-wave mixing (FWM) generation by the fast light effect in the bandgap of fiber Bragg grating. Energy conversion out of the bandgap has been realized in a low power level. The experimental result shows great agreement with the simulation.

Keywords: Nonlinear optics, fibers, four-wave mixing, Fiber Bragg gratings

1. INTRODUCTION

Photonic bandgap can be created in various kinds of periodic photonic media. Photons with energies lying in the bandgap cannot propagate through the medium. [1] Thus any kind of phenomena related with light transmission including nonlinear effects such as four-wave mixing (FWM) is regard as impossible. Furthermore, the forward and backward waves are coupled in the photonic bandgap, a standing wave is formed and net transmission of energy is prohibited. In order to convert energy out of the bandgap, a variety of methods have been applied to enhance the transmissivity in the photonic bandgap [2], [3]. However, high power (~1kW) employed in these experiments remains this kind of energy conversion unfeasible.

2. PRINCIPLE AND SIMULATIONS

More than a method of controlling the speed of light in most of the cases, the slow/fast light effect[4], [5] offers a novel way to fulfill the above mentioned task in a low energy level in the following way. With the propagation coefficient $\beta$ expanded to the second order in a Taylor series, optical phase is written as

$$\varphi = \beta z + \beta_1 (\omega - \omega_0) z + \frac{1}{2} \beta_2 (\omega - \omega_0)^2 z$$

(1)

When group velocity dispersion (GVD) $\beta_2 = d^2 \beta / d \omega^2$ is considered, the 1st derivation of propagation coefficient, which is equal to the reciprocal of the group velocity $v_g$, i.e., $\beta_1 = d \beta / d \omega = 1 / v_g$ is no longer constant. This indicates, the change of group velocity leads to an extra phase along propagation $\Delta \varphi = \Delta \beta z$, and thus optical phase can be manipulated. FWM is a phase-match dependent optical nonlinear effect without threshold [6], so that its efficiency can be enhanced by introducing such an extra phase to satisfy the phase-match condition. Conventionally, it is the slow-light effect that is used to enhance nonlinear effect owing to the increase of power density[7], but the fast light is not.

In our work, fast light effect in the photonic bandgap of fiber Bragg grating (FBG) is used to control the optical phase. Simulations as well as experiments with a special-designed FBG for phase-matched FWM generation were carried out, and FWM process in the photonic 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 (~200mW), our scheme involves little interference from unnecessary nonlinear effects.

It is well known that, FBG is a device of photonic bandgap. Owing to strong chromatic dispersion introduced close to or in the photonic bandgap[1], [8], the optical phase varies rapidly[9] and therefore causes a considerable group delay or advancement. The feature of a uniform FBG can be obtained by the amplitude reflection coefficient [9]. Since the group delay in transmission equals to the one in reflection [10], the group delay transmitted through a FBG can be expressed as [11]

$$\tau(\lambda) = \tau(\lambda) = -\frac{\lambda^2}{2 \pi c} \frac{d \varphi}{d \lambda}$$

(2)

where $\lambda$ is the wavelength, $\varphi$ is the transmission phase, and $c$ is the light speed in vacuum. Due to the same phase shifts introduced in both propagation directions, forward and backward waves remain coupled with each other[12]. Therefore, even if the slow/fast light effect is considered, forward transmission in the FBG photonic bandgap is still prohibited.

As shown in Fig.1, we measured the transmission features of a Gaussian-apodized FBG with a length of 10 cm. The group 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. Discontinuity in the optical
phase results in the slow/fast light effect near or in the bandgap.

Fig.1. Transmittivity and group delay of the FBG. Inset is the plot of the optical phase. Due to the limit of detection sensitivity, fluctuation of transmission occurs in the bandgap.

Without considering other nonlinear effects under low pump level, a degenerated FWM is controlled by the phase-match condition as

$$\Delta \beta = 2 \beta_p - \beta_s - \beta_i$$

where $\beta_p, \beta_s, \beta_i$ are the propagation coefficients of the pump, signal, idler wave, respectively. With the manipulation of the propagation coefficient via group velocity control, the phase-match condition $\Delta \beta = 0$ can be achieved.

Fig.3 shows the experiment scheme, in which two incident lights with different wavelength were emitted by two tunable laser sources (TLS). Two Erbium-doped fiber amplifiers (EDFAs) amplified two lasers as the pump and signal waves of FWM. The above mentioned FBG with a length of 10 cm, Bragg wavelength at 1550.186 nm, 3 dB bandwidth 0.158 nm, provided the incident light aimed at its bandage an appreciable delay as well as advancement in the photonic bandgap. Through 1% port of a 99:1 optical coupler (OC), the FWM spectrum was monitored by an optical spectrum analyzer (OSA).

Experiment was carried out by setting the wavelength of one TLS input light at 1551.28 nm, while the wavelength of the other input light was fine tuned from 1549.84 nm to 1550.41 nm, which covered the whole FBG bandgap region. Through the spectrum of output port of OC2, changes of idler wave power during the sweep were observed.

As the results show in Fig.4, when pump light aimed at the edge of FBG at 1550.11 nm, and thus experienced a group delay of 68.48 ps, idler wave power in both sides suffered a decrease, i.e., 1.11 dB on shorter
wavelength and 1.33 dB on longer wavelength side. As the pump wave moved to 1550.26nm, and experienced a delay of 62.75 ps, idler wave power in both sides dropped, by 1.21 dB in shorter wavelength and 1.67 dB in longer part. Whereas, while the pump light was fully reflected and thus got an advancement of 68.71 ps in the photonic bandgap, the fast light effect partly compensated the loss of idler wave power in shorter wavelength and even helped the longer part back up to the power level outside the photonic bandgap. In contrast, due to the phase-mismatch and short length of fiber[6], FWM generation was not observed with the substitution of a single-mode fiber with the same length to the FBG in this experiment. The experimental result showed a good agreement with our simulation.

![Fig.4. Experimental results, the superposition of FWM spectrums with different pump wavelengths. Variation of idler power result from the slow/fast light effect in FWM. Inset (a) and (b) illustrate the spectrum of left and right idler spectra respectively.](image)

4. CONCLUSION

Chromatic dispersion introduced in the photonic bandgap of a typical FBG is roughly 6 orders of magnitude larger than that of bare fiber at 1550nm[14], therefore the slow/fast light effect is easy to observe in this strong dispersion regime. The FWM enhancement of several orders of magnitude can be expected by using an FBG as long as magnitude of meter. Furthermore, this theory also suits photonic bandgaps in other structures, thus we believe that, a series of other propagation-related nonlinear effects in the photonic bandgap can be realized by means of the slow/fast light effect.

In conclusion, we have proposed and demonstrated the FWM generation in the photonic bandgap. Energy conversion of a standing wave to the channels out of the photonic bandgap was observed for the first time to our knowledge. By introducing extra phase shift via the fast light effect, we have made this impossible process possible. With the help of this 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.

5. ACKNOWLEDGMENTS

The authors acknowledge the support from the National Natural Science Foundation of China (Grants 61178014/11274231/61308003).

6. REFERENCES