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Phase variation of fundamental field induced by cascaded second order nonlinear processes in KTP

YUJIE HU, DUANZHENG YAO

Department of Physics, Wuhan University, Wuhan 430072, China; e-mail: dzyao@whu.edu.cn

In this paper it has been demonstrated by numerical simulation that the intense second harmonic field induces a nonlinear phase change on a fundamental field simultaneously through the cascaded second-order processes. It has been shown that the phase variation depends on both the propagation distance and the incident fundamental field E_1. The phase variation strongly depends on the wavelength of the fundamental field. With the increase of the wavelength of the fundamental field, most of the phase variation induced by the second harmonic wave on the fundamental wave becomes smaller linearly. It has been also shown that there are some nonlinear regimes in the phase variation. For some wavelengths of the fundamental field, there are some peaks of the decrease or increase of the induced phase variation.

Keywords: induced phase variation, cascaded second-order processes, the fundamental field, the second-harmonic field.

1. Introduction

During the past decade, the cascaded second-order nonlinearity (CSN) in which second -order nonlinear effects generate an intensity dependent phase shift has attracted considerable research attention [1]. Most cascaded effects studied are based on SHG in which both the fundamental and the second harmonic fields are guided [2]. There has been some works in which the CSN processes have been used in a variety of arrangements. For example, a novel and simple Erbium-doped fiber laser using cascaded fiber Bragg gratings (FBG) written in high-birefringence fibers for switchable multi-wavelength operation has been proposed. Experimental results show that the stable dual- and three-wavelength lasing operation with very narrow wavelength separation can be generated at room temperature [3]. Multi-channel wavelength conversion through the cascaded second-order nonlinear processes in periodically poled lithium niobate waveguide in the optical communication wavelength band of 1.5 μm is experimentally demonstrated [4]. It has been shown that type I CSN processes can simulate a self-diffraction process and achieve efficiencies much higher than those obtainable in third-order self-diffraction for a given input intensity [5]. The parametric amplification of a weak probe pulse via CSN processes was also discussed [6]. Recently, it has been demonstrated that an intense second harmonic field induces a nonlinear phase-shift on a weak fundamental field simultaneously exciting a SHG crystal detuned from phase-matching, through cascaded second order processes. It has been shown that, for sufficiently large detunings, this particular interaction weakly depends on the initial phase relationship between inputs [7]. Nonlinear phase shifts of the fundamental beam in the quasi-phase matched Cerenkov (QPMC) configuration in waveguides as a function of length of interaction and grating period have been obtained by using the coupled mode analysis [8].

In this paper, the phase variation induced by the second harmonic wave on the fundamental wave through cascaded second-order processes in nonlinear crystal has been investigated numerically. It is shown that the phase variation depends on both the propagation distance and the power density of the input fundamental field E_1. The phase variation strongly depends on the wavelength of the fundamental field.

2. Induced phase variation

A nonlinear crystal (KTP) is excited by an intense field with the harmonic frequency 2ω and by a weak signal with the fundamental frequency ω simultaneously.

In order to analyze the nonlinear phase change of the fundamental wave at frequency ω induced by the second harmonic wave in nonlinear crystal, the method of the coupled nonlinear wave equations has been used. The coupled wave equations describing the fundamental and second harmonic fields can be written approximately as follows [8]:

$$\frac{\mathrm{d}E_1}{\mathrm{d}z} = -i\frac{\omega}{4cn_\omega}\chi^{(2)}(\omega; 2\omega, -\omega)E_1^* E_2 \exp(-i\Delta kz), \tag{1}$$

$$\frac{\mathrm{d}E_2}{\mathrm{d}z} = -i\frac{\omega}{2cn_{2\omega}}\chi^{(2)}(2\omega; \omega, \omega)E_1 E_1 \exp(i\Delta kz) \tag{2}$$

where E_1 stands for the complex amplitude of the field at the fundamental frequency and E_2 stands for the complex amplitude of the field at the second harmonic generation; $\Delta k = 2\omega(n_{2\omega} - n_\omega)/c$ represents the phase mismatch.

In order to get the phase change of the fundamental wave at frequency ω, induced by the second harmonic wave in nonlinear crystal, E_1 should to be independent of z. By solving the Eq. (2), the complex amplitude of the second harmonic field E_2 is obtained. Then substituting E_2 in Eq. (1), by an iterative procedure of incremental steps of propagation distance, the variation of the induced phase change along the propagation length can be obtained.

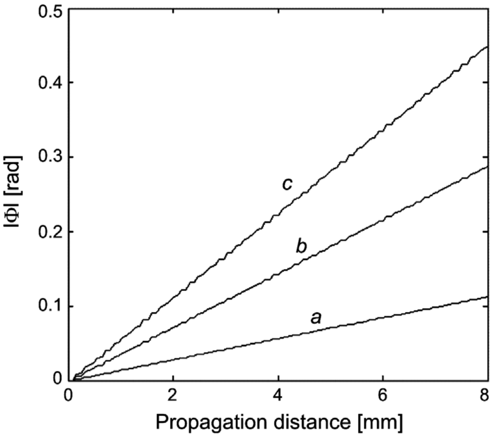

Fig. 1. Induced phase variation as a function of the propagation distance for different input fundamental power densities: 0.5×10^8 V/m (*a*), 0.8×10^8 V/m (*b*) and 1×10^8 V/m (*c*).

In the numerical calculations, the case of KTP with $d_{\mathrm{eff}} = 3$ pm/V is considered, the propagation distance is 8 mm, and the wavelength of the fundamental wave is 1064 nm.

Figure 1 shows the variation of the nonlinear phase change with propagation distance for several input fundamental power densities E_1: 0.5×10^8, 0.8×10^8 and 1×10^8 V/m. The induced phase variation increases linearly with the increase of propagation distance for a definite intensity of the incident wave at the fundamental wavelength. Due to the different input fundamental power density, the linearly increases of the induced phase change are different. This is illustrated in Fig. 1. Then the variation of the induced phase change becomes more and more fast with respect to the propagation distance when the incident fundamental power density E_1 is increasing, and is more dependent on the incident fundamental power density.

3. Induced phase variation with different wavelengths of the fundamental field

In the simulations of induced phase change with different wavelength of the fundamental, the wavelength from 900 to 1200 nm is considered. The propagation distance is still at 8 mm.

Most of the phase change induced by the second harmonic wave on the fundamental wave through cascaded second-order processes in nonlinear crystal is linear with respect to the wavelength of the fundamental. With the increase of the wavelength of the fundamental, the phase change becomes smaller. But, there are some nonlinear regimes in the phase change shown in Fig. 2. For example, when the wavelengths of the fundamental are 920, 950, 1000, 1040, 1130 and 1180 nm, the induced phase changes

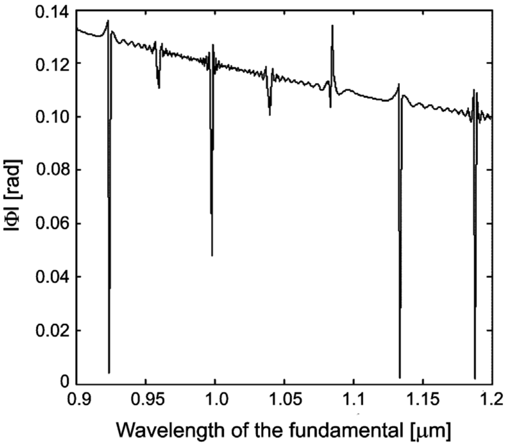

Fig. 2. Phase change induced by the second harmonic wave on the fundamental wave through cascaded second-order processes as a function of the wavelength of the fundamental and for the propagation distance of 8 mm.

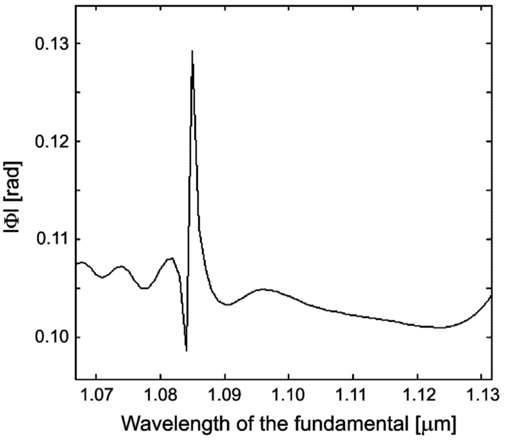

Fig. 3. Peak of the increase of the induced phase change as a function of the wavelength of the fundamental. The value of the peak is about 0.13.

are unusual and are different to those at other wavelengths. There are some peaks in which the induced phase change has been decreased at these wavelengths of the fundamental. The induced phase change even decreases to zero. The widths of these peaks at these wavelengths are about 2 to 3 nm.

This is in contrast with the case in which there is a peak of the increase of the induced phase change in the wavelength of the fundamental field 1085 nm. And the peak of the increase of the induced phase change exhibits different nonlinearity. The specific situation is shown in Fig. 3. The value of the peak is 0.13. On the left of the peak, close to the wavelength of the fundamental, the phase change induced by

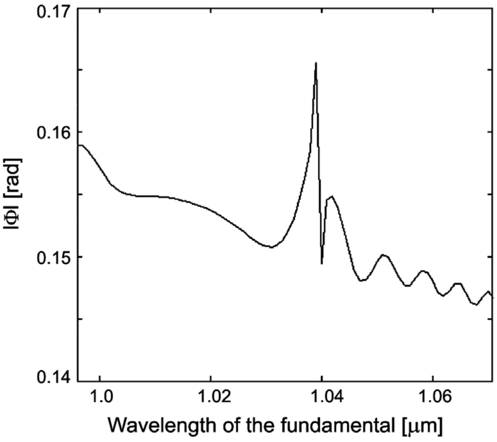

Fig. 4. Phase change induced by the second harmonic wave on the fundamental wave through cascaded second-order processes as a function of the wavelength of the fundamental and for the propagation distance of 8 mm and refractive indices $n_{2\omega} - n_{\omega} = 0.130$.

the second harmonic wave on the fundamental wave through cascaded second-order processes in nonlinear crystal is not smooth with the wavelength of the fundamental wave. On the contrary to the left of the peak, on the right of the peak, the phase change moves smoothly with the wavelength of the fundamental.

Figure 4 shows the phase change with respect to the wavelength of the fundamental for different refractive indices. In contrast to the case in Fig. 2 of refractive indices $n_{2\omega} - n_{\omega} = 0.156$, the relation between refractive indices in Fig. 4 is $n_{2\omega} - n_{\omega} = 0.130$. It is shown that the induced phase change is nonlinear with respect to the wavelength of the fundamental. For the same wavelength of the fundamental wave and for the same propagation distance, the induced phase change is different because of different refractive indices. In Fig. 4, there is a peak of the increase of the induced phase change at the wavelengths of the fundamental 1040 nm, and the value of the peak is 0.166. On the right of the peak, the variation of the phase change is not smooth with the wavelength of the fundamental. On the contrary to the right of the peak, on the left of the peak, the phase change moves smoothly with the wavelength of the fundamental that is different from the case in Fig. 3. The phase change with the wavelength of the fundamental in Fig. 4 decreases more quickly and is also different from the case in Fig. 3.

4. Conclusions

In this paper it has been demonstrated by numerical simulation that the intense second harmonic field induces a nonlinear phase change on a fundamental field simultaneously through cascaded second order processes.

It has been shown that the phase change depends on both the propagation length and input fundamental power density E_1. The induced phase change increases linearly with the increase of propagation distance. When the input fundamental field E_1 is increasing, the variation of the induced phase change is more dependent on the input fundamental power density. The phase change strongly depends on the wavelength of the fundamental. It has been shown that the induced phase change is different for different wavelength of the fundamental at a fixed propagation distance. With the increase of the wavelength of the fundamental, most of the phase change induced by the second harmonic wave on the fundamental wave becomes smaller linearly. There are also some nonlinear regimes in the phase change. For some wavelengths of the fundamental, there are some peaks of the decrease and increase of the induced phase change. The induced phase change even decreased to zero. The peak of the increase of the induced phase change exhibits different nonlinearity. Moreover, it is shown that the phase change is also dependent on the refractive indices. It should be mentioned that the results could be useful in research studies devoted to cascade second order nonlinearity.

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