

# Effect of Absorption on The Efficiency of THz Radiation Generation in a Nonlinear Crystal Placed Into a Waveguide

(Proceedings of the Int. Conference on “ Microwave and THz Technologies and Wireless comm.”)

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Received 15 November 2018

**Abstract:** The effect of THz radiation absorption on the efficiency of generation of coherent THz radiation in a nonlinear optical crystal placed into a metal rectangular waveguide is studied. The efficiency of the nonlinear conversion of optical laser radiation to the THz band is also a function of the phase-matching (PM) condition inside the nonlinear crystal. The method of partial filling of a metal waveguide with a nonlinear optical crystal is used to ensure phase matching. Phase matching was obtained by the proper choice of the thickness of the nonlinear crystal, namely the degree of partial filling of the waveguide. We have studied the THz radiation attenuation caused by the losses in both the metal walls of the waveguide and in the crystal, taking into account the dimension of the cross section of the waveguide, the degree of partial filling and its dielectric constant.

**Keywords:** Nonlinear crystal, phase-matching, femtosecond laser, single-layer reflection.

## 1. Introduction

Waveguides containing dielectric inserts find applications in many waveguide components [1]. It has been shown that the method of measuring the absorption of a dielectric, which partially fills a waveguide, is 50 times more sensitive than the traditional method of single-layer reflection [2]. Efficient generation of ultra-short THz pulses in a nonlinear crystal, partially filling a rectangular waveguide, using pico- or femtosecond laser pulses was proposed and performed in [3-5]. The generation of the THz pulse is based on the mixing of the spectral components of a femtosecond optical laser pulse in a nonlinear crystal (optical rectification method). The method of partial filling of a metal waveguide with a nonlinear optical crystal was used to ensure phase matching (PM).

The influence of THz radiation absorption on the efficiency of generation of coherent THz radiation in a nonlinear optical crystal placed into a metal rectangular waveguide (Fig.1) is presented here. The efficiency of the nonlinear conversion of optical laser radiation to the THz range is also a function of the PM condition in the nonlinear crystal, i.e of the equality of the group velocity of the optical pulse and of the phase velocity of the THz pulse at the difference frequency. Phase matching was obtained by the proper choice of the thickness of the nonlinear crystal, namely the degree of partial filling of the cross section of the waveguide.

The THz radiation attenuation caused by the losses both in the metal walls of the waveguide and in the crystal was calculated taking into account the dimensions of the cross section of the waveguide, the thickness of the crystal (the degree of partial filling) and its dielectric constant. DAST,  $LiNbO_3$  and  $ZnTe$  crystals were studied due to their high efficiency of conversion of optical radiation into the THz range. These crystals have a high second-order nonlinear susceptibility and various dielectric constants for which the condition PM is satisfied.

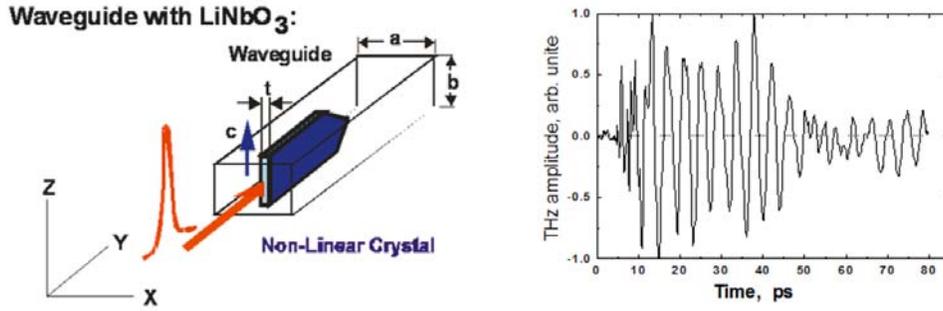


Fig.1. Nonlinear crystal LiNbO<sub>3</sub> in a metal rectangular waveguide (a), THz pulse (b)

## 2. THz radiation attenuation caused by the losses in the metal walls of the waveguide and in the crystal

The attenuation coefficient in the metal walls of a waveguide partially filled by a nonlinear crystal is determined from expression (1):

$$\alpha_m = m \frac{a}{b} \left\{ \left( \frac{\epsilon_0 \mu_0}{m^2} - 1 \right) \frac{1}{R_1} \left[ R_2 + 2 \frac{b}{a} \left( \frac{\cos \beta t}{\sin \alpha d} \right)^2 \right] + 1 \right\} \frac{R_s}{a Z_0}, \quad (1)$$

where

$$R_1 = \frac{2t}{a} \left( 1 + \frac{\sin 2\beta t}{2\beta t} \right) + \left( 1 - \frac{2t}{a} \right) \left( \frac{\cos \beta t}{\sin \alpha d} \right)^2 \left( 1 - \frac{\sin 2\alpha d}{2\alpha d} \right),$$

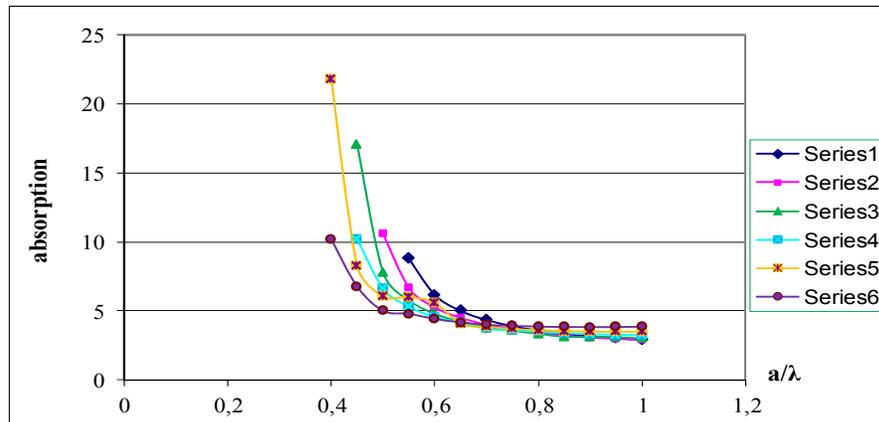
$$R_2 = \frac{2t}{a} \left( \frac{\beta}{\alpha} \right)^2 \left( 1 - \frac{\sin 2\beta t}{2\beta t} \right) + \left( 1 - \frac{2t}{a} \right) \left( \frac{\cos \beta t}{\sin \alpha d} \right)^2 \left( 1 + \frac{\sin 2\alpha d}{2\alpha d} \right),$$

$$R_3 = \sqrt{\omega \mu / 2 \sigma},$$

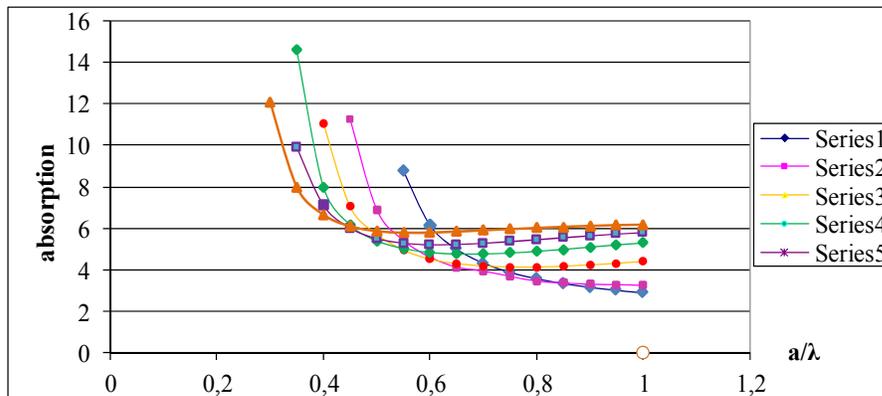
$m = \lambda / \lambda_{wG}$  is the deceleration factor of an electromagnetic wave,  $\lambda$  is the wavelength in a free space,  $\lambda_{wG}$  is the wavelength in the waveguide,  $a$  and  $b$  are the width and height, respectively, of the rectangular waveguide,  $d$  is the distance from the narrow wall of the waveguide to the crystal,  $2t$  is the thickness of the crystal,  $\alpha = 2\pi / \lambda \sqrt{\epsilon_0 \mu_0 - m^2}$ ;  $\beta = 2\pi / \lambda \sqrt{\epsilon \mu - m^2}$  and  $Z_0 = \sqrt{\mu_0 / \epsilon_0} = 377 \Omega$  is the impedance of the free space,  $\sigma$  is conductivity of waveguide walls. The attenuation determination was performed for various crystal fillings  $2t/a$ . Nonlinear crystals DAST ( $\epsilon = 5.2$ ); ZnTe ( $\epsilon = 10.1$ ); LiNbO<sub>3</sub> ( $\epsilon = 26.5$ ) were investigated, with different dielectric constant and high figures of merit (FOMs [6]) used for generation of THz pulse. The losses in an empty waveguide depend on the ratio of the width of the waveguide to its height and are minimal when  $a/b = 2$ . In expression (2) the values of  $a = 2.4 \text{ mm}$ ,  $b = 1.2 \text{ mm}$  are substituted. It should be noted that in the case of a small dielectric permittivity (DAST ( $\epsilon = 5.1$ )) and partial filling, there are cases when the losses in the metal walls are comparable to the losses in the walls of an unfilled metal waveguide.

Figure 2 shows that for a DAST crystal with a low dielectric constant, in the case of  $2t/a \leq 0.15$  and  $a/\lambda > 0.65$ , the loss in the metal wall is comparable to the loss in the empty waveguide, that is, the waveguide does not distort the pulse in the frequency range of waves of the main type. In addition, in the case of a thin crystal with a low dielectric permittivity, attenuation can be weaker than in an unfilled waveguide for  $a/\lambda$  from 0.4 to 0.8. In a partially filled waveguide, this effect is due to the decrease of the cut-off frequency.

In the case of a high dielectric constant of the crystal, the losses in the waveguide walls are higher, and the attenuation depends more on the degree of filling with a crystal,  $2t$ , than on ratio of  $a/\lambda$ , i.e. the frequency.



**Fig.2.** Attenuation in a metallic waveguide partially filled with a DAST crystal,  $\epsilon^e = 5.2$ , for  $2t/a = 0$  (Series1);  $2t/a = 0.025$  (Series2);  $2t/a = 0.05$  (Series3);  $2t/a = 0.075$  (Series4);  $2t/a = 0.1$  (Series5);  $2t/a = 0.15$  (Series6).



**Fig.3.** Attenuation in a metallic waveguide partially filled with a ZnTe crystal,  $\epsilon^e = 10.1$ , for  $t/a = 0$  (Series1);  $2t/a = 0.025$  (Series2);  $2t/a = 0.05$  (Series3);  $2t/a = 0.075$  (Series4);  $2t/a = 0.1$  (Series5);  $2t/a = 0.15$  (Series6);  $a = 2.4$  mm.

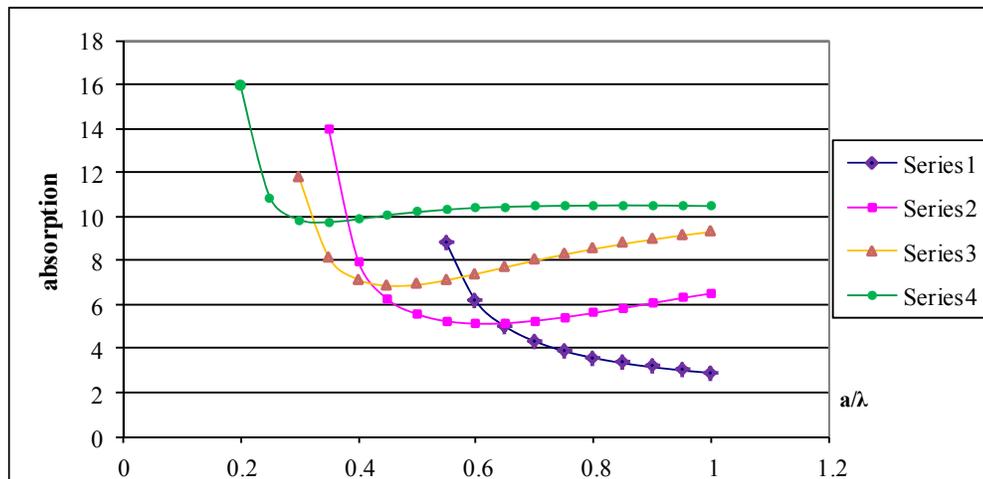


Fig.4. Attenuation in a metallic waveguide partially filled with a  $LiNbO_3$  crystal,  $\epsilon^e = 26.5$ , for  $2t/a = 0$  (Series1);  $2t/a = 0.025$  (Series2);  $2t/a = 0.05$  (Series3);  $2t/a = 0.15$  (Series4).

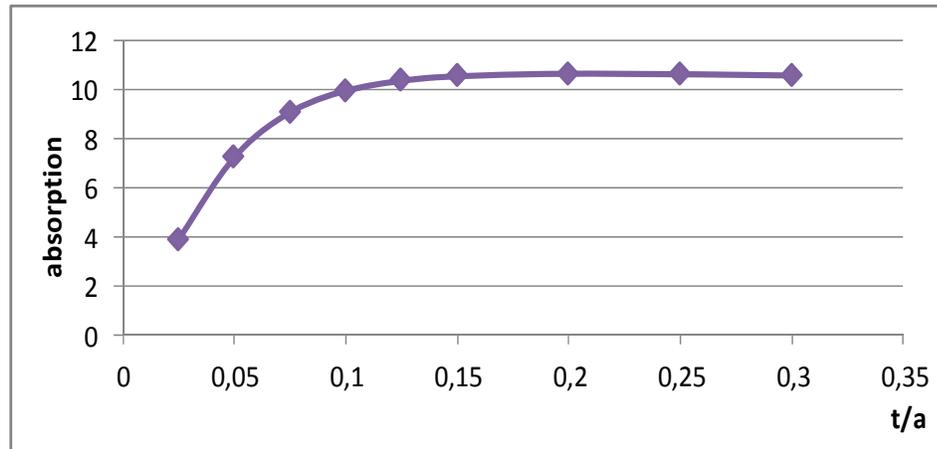
The attenuation in the walls of a waveguide with a  $LiNbO_3$  crystal is less than in an empty waveguide in the wavelength range of  $0.5 < a/\lambda < 0.65$ . Thus, THz pulses or waves can be generated in a narrow frequency range with an attenuation less than that in an empty waveguide. In this frequency band, the pulse will not be attenuated and broadened in a waveguide.

The attenuation due to losses in a crystal, partially filling a waveguide, was determined from the expression (2)

$$\alpha_d = \epsilon \frac{\pi a}{m \lambda R_1} \frac{1}{a} \frac{2t}{a} \left( 1 + \frac{\sin 2\beta t}{2\beta t} \right) / \frac{a}{tg \delta}, \quad (2)$$

where  $tg \delta = \epsilon''/\epsilon'$ . The attenuation constant shown in Fig. 5 is  $\alpha = \alpha_d \cdot tg \delta / a$ , ( $\alpha_d$  in units of  $Np/m$ ). The figure illustrates that the attenuation of THz pulses increases with the degree of filling of the given cross-section of a waveguide.

The obtained data mean that a threefold reduction of the attenuation of a given frequency is possible if a partially filled waveguide is used instead of a completely filled one. Reducing the attenuation in turn allows the use of crystals of greater length than in the case of complete filling of the waveguide. This results in a double effect. The partially filled waveguide makes it possible to ensure the condition of phase matching as well as reduces the loss of THz radiation due to absorption in the generating crystal. This cannot be achieved by other methods providing phase matching, when a non-linear crystal is located in a free space where the attenuation coefficient is a constant value. Thus, a waveguide partially filled with a nonlinear crystal, will ensure efficient generation of THz radiation due to phase matching and less absorption in the crystal.



**Fig.5.** Attenuation constant in the waveguide partially filled with a  $\text{LiNbO}_3$  crystal for  $2t/a$  varying in (0; 1) interval.

### 3. Conclusion

Generation efficiency in the process of converting the frequency of ultrashort laser pulses to the THz range depends on the fulfillment of the phase matching condition as well as on the losses ( $\alpha_s = \alpha_m + \alpha_d$ ) at a given crystal length. DAST,  $\text{LiNbO}_3$  and  $\text{ZnTe}$  crystals were studied due to the high efficiency of conversion of optical radiation to THz range in a waveguide partially filled with one of these crystals.

It is shown that the attenuation of THz pulses increases with the degree of filling of the given cross-section of a waveguide by crystal (Fig.5). However, in the case of a small dielectric permittivity and partial filling, the losses in the metal walls are comparable to the losses in the walls of an unfilled metal waveguide. Moreover, in the case of a thin crystal with low dielectric permittivity, attenuation can be weaker than that in an unfilled waveguide. In a partially filled waveguide, this phenomenon occurs because of the decrease of the cut-off frequency, which is more obvious when the waveguide is completely filled with a crystal. In the case of a high dielectric permittivity of the crystal, the losses in the walls of the waveguide are observed to be higher, which is more due to the degree of filling with the crystal than due to the ratio of  $a/\lambda$ , i.e. from the frequency. In all crystals, minimum attenuation is observed for a certain frequency band.

### Acknowledgments

This work was supported by the Ministry of Education and Science of Russian Federation, under contract №14.583.21.0069, RFMEFI58317X0069

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