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INTERFERENCE EFFECTS IN MICROCHIP LASER WITH INTRACAVITY FREQUENCY DOUBLING

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The temperature dependence of output power of microchip laser with intracavity frequency doubling is investigated, where oscillations in the output power are observed. Similar oscillations are observed in the temperature tuning of single pass second harmonic generation in plane parallel nonlinear crystal. It is supposed that in both two cases the oscillations have the same origin. Single pass second harmonic generation is investigated experimentally and theoretically, and it is shown that oscillations are due to multiple beam interference in the nonlinear crystal. Results of the experiments and calculations are presented.

Keywords: Microchip laser, quasi-phase matching, optical second harmonic generation, intracavity frequency doubling.

1. Introduction

Second harmonic generation (SHG) in a nonlinear plane parallel slab has been treated for the first time by Bloembergen and Pershan in 1962 [1], where they took into account the boundary conditions at a plane interface between a linear and nonlinear medium. Since then, interference effects in SHG have been investigated extensively. Several authors report on oscillating behavior of SHG power as a function of wavelength or thickness of the crystal in case of single pass second harmonic generation [2–6]. SHG in plane parallel nonlinear crystal is of interest for us, because it plays important role in the microchip laser with intracavity frequency doubling.

To the best of our knowledge, there are no published papers on the temperature dependence of interference effects in SHG in plane parallel nonlinear crystal. The motivation for this work is the development of green microchip lasers. Microchip laser with intracavity frequency doubling is of great interest, because it is an efficient, powerful and miniature source of green (532nm) light. The cavity of the laser is composed of two planar components: gain crystal is a Nd^{3+}:YVO_4 (YV) and nonlinear crystal is a periodically polled MgO:$LiNbO_3$ (PPLN) [7]. These crystals are optically contacted. Mirrors of the cavity are formed by dielectric coatings directly applied to the crystal surfaces. Input mirror is high reflective (HR) at both fundamental (1064nm) and second harmonic wavelengths (532nm) and anti-reflective (AR) at pump wavelength (808nm). Output mirror is AR at 532nm and HR at 1064nm. Efficiency of pumping depends on the temperature. We use 808nm absorption peak of the YV. Full width at half maximum (FWHM) for π-polarization absorption peak is about 1.8nm. Laser diodes at 808nm are used as a pumping source. The emitting wavelength of these diodes strongly depends on the temperature (typically $d\lambda_{em}/dT \approx 0.3\text{nm}/^{\circ}\text{C}$). Therefore, only 3°C variation of the temperature will halve the peak absorption coefficient. The efficiency of quasi-phase-matched SHG in the nonlinear crystal also strongly depends on the temperature. Thus, investigation of the temperature dependence of microchip laser output power is important in order to improve the energy conversion efficiency and power stability.

2. Temperature dependence of microchip output intensity

To investigate temperature dependence of microchip output, we performed a series of experiments, where the temperature of the laser diode was kept constant with precision of 0.1°C, to avoid fluctuation of the pump wavelength. Temperature of the microchip laser was changed in the range of 20 – 60°C and output intensity was registered at different temperatures. The experimental setup is depicted in Fig.1.

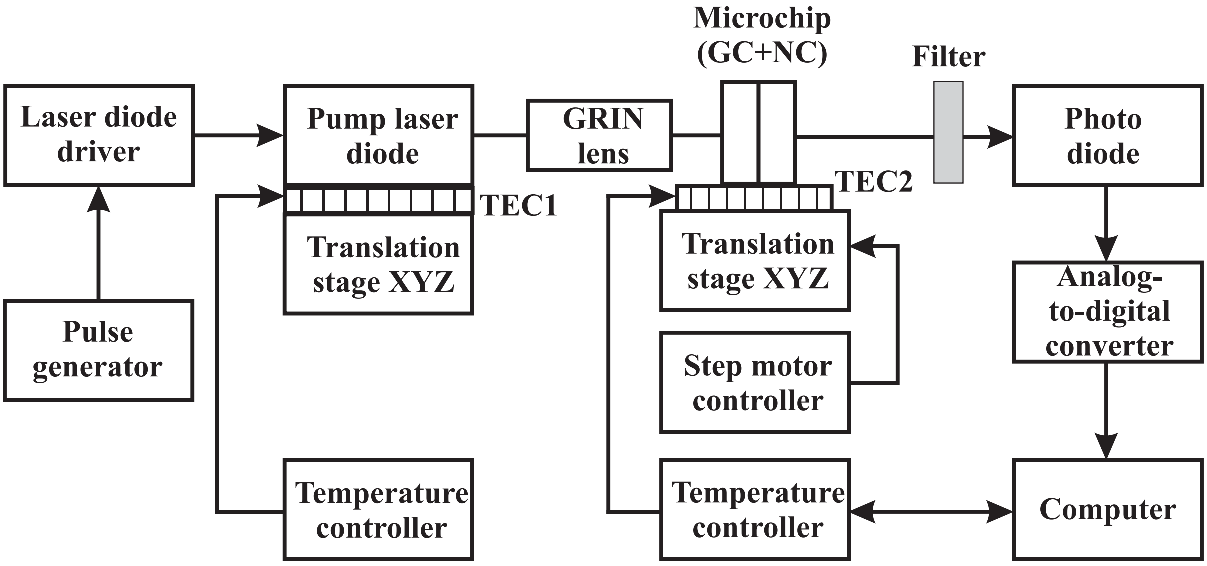
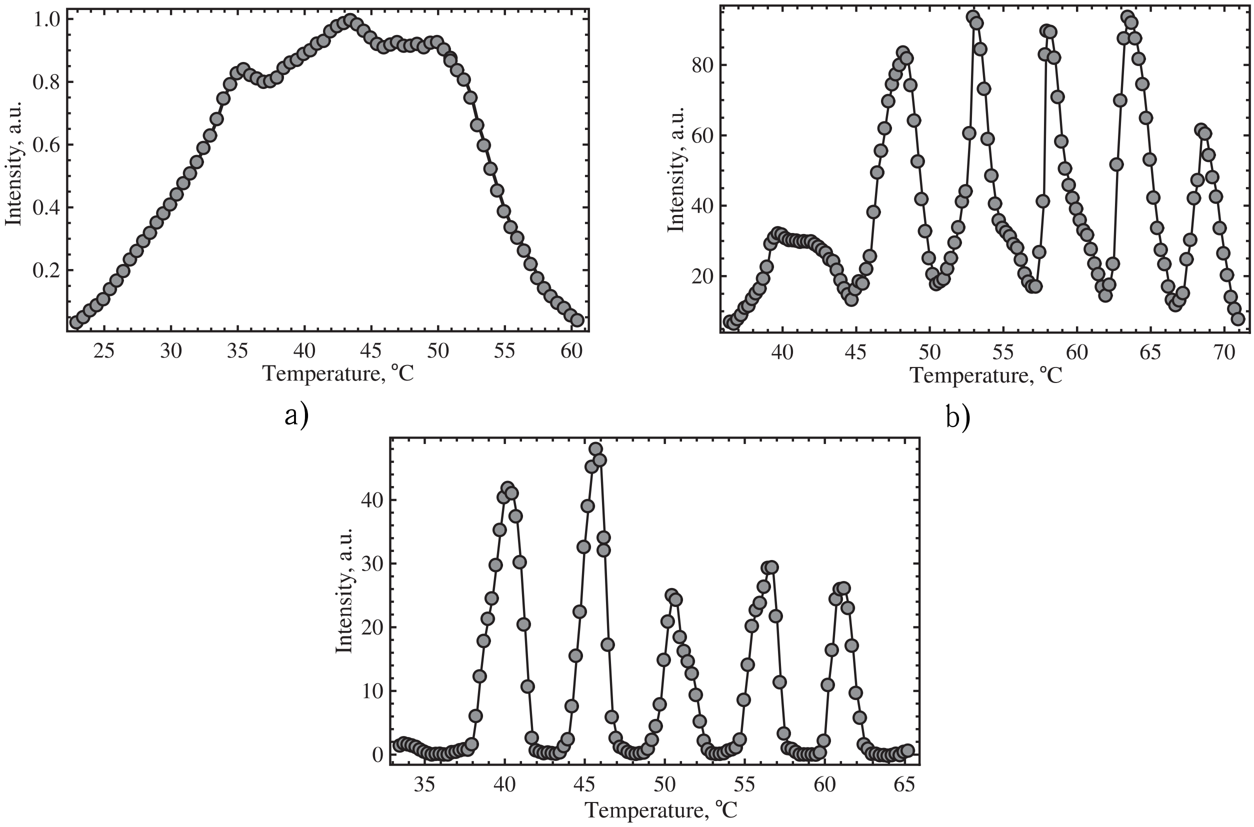


Fig. 1. Experimental setup for measuring temperature dependence of microchip output power

Measurement results are presented in Fig. 2. It can be seen, that there are two kinds of temperature dependence of laser power. The first one (Fig. 2a) is a relatively smooth curve, and two others (Fig. 2b and c) have distinct periodic oscillations. The oscillation period is typically $\tau = (5.4 \pm 0.5)^\circ$ C.

We suppose that oscillations are a result of multiple beam interference in the nonlinear crystal. The most probable reason for the difference in the performance of three microchips shown in Fig. 2 is different residual reflection from the interface between the gain crystal and the nonlinear crystal. For perfect optical contact, the Fresnel reflection from the interface is negligible because the refractive indices of YV and PPLN are nearly equal. The ratio of two refractive indices is 1.032, which gives about $10^{-4}\%$ Fresnel reflection for normal incidence. However, imperfect optical contact (contamination, air bubbles etc.) may lead to higher residual reflection from the interface. We have developed a method for measuring reflection from the interface in high finesse resonator [8], and it was shown that microchips with oscillating behavior have notable reflection from the optically contacted interface, typically higher than 2%. To understand the origin of oscillations observed in the temperature dependence of microchip laser power, we performed theoretical and experimental study of single pass SHG in a plane parallel nonlinear crystal, identical to that used in the microchip laser.



a) b)

c)

Fig. 2. Measurement results of temperature dependence of output power for three different microchips: a) Relatively smooth curve, b,c) Curves with periodic oscillations

3. Single pass SHG

In this section, calculations of the temperature dependence of SHG intensity in a plane-parallel nonlinear crystal are presented and compared to experimental results.

First, the wave equation for second harmonic field is solved [9].

$$\frac{d^2}{dz^2}E_2(z) - \frac{\omega_2^2}{c^2}\varepsilon_2 E_2(z) = \frac{4\pi\omega_2^2}{c^2}P_{NL}(z) \tag{1}$$

where $E_2(z)$ is the electric field of SH wave inside the nonlinear crystal, $P_{NL}(z) = 4d_{eff}E_1^2(z)$ is the nonlinear part of the polarization, d_{eff} is the effective nonlinear susceptibility, $E_1(z)$ is the electric field of the fundamental wave inside the nonlinear crystal, ε_2 is the dielectric susceptibility of the crystal for second harmonic wave, ω_2 is the frequency of the second harmonic wave, c is the speed of light.

Inside the nonlinear crystal, the electric field of the fundamental wave is the sum of multiple reflected waves from the boundaries of the crystal, thus solution of the wave equation is also sought in the form of sum of two waves, propagating in opposite directions $E_2(z) = A_2^+(z)e^{ik_{2\omega}(z)} + A_2^-(z)e^{-ik_{2\omega}(z)}$. To take into account interference between second harmonic waves, we should take into account reflections from the boundaries of the crystal, and write down the appropriate boundary conditions.

$$\begin{cases} A_2^-(l) = r_{2,2\omega} A_2^+(l) e^{2ik_{2\omega}l} \\ A_2^+(0) = r_{1,2\omega} A_2^-(0) \end{cases} \tag{2}$$

where $A_2^+(z)$ and $A_2^-(z)$ are amplitudes of electric field of the second harmonic wave propagating forward and backward in the crystal. $r_{1,2\omega}$ and $r_{2,2\omega}$ are amplitude reflection coefficients of first and second boundaries of the nonlinear crystal for second harmonic wave, l is the length of the crystal. Equation (1) is solved under the following approximations:

(1) *Plane wave*. We consider fundamental and second harmonic waves as plane waves.
(2) *Undepleted pump*. We consider that fundamental wave amplitude is constant during the propagation through the nonlinear medium, or in other words, second harmonic power is negligible compared to the fundamental power.
(3) *Slowly varying amplitude*. We assume that $|d^2A_2/dz^2| \ll |k_2(dA_2/dz)|$. This approximation allows us to reduce the order of differential equation and (2) boundary conditions will be enough to solve it.

Output intensity of the second harmonic wave is equal to

$$I_2 \propto \frac{64\pi^2 {d_{eff}}^2 \omega_2^4}{c^4} l^2 |E_0|^4 \text{sinc}^2\left(\frac{\Delta kl}{2}\right)(FP_\omega)^2 FP_{2\omega} \tag{3}$$

where: $\Delta k = 2k_\omega - k_{2\omega} - 1/\Lambda$ is the phase mismatch, k_ω and $k_{2\omega}$ are wave vectors of the fundamental and second harmonic waves Λ is the domain period of the periodically polled nonlinear crystal, in case of quasi-phase matched second harmonic generation, E_0 is the amplitude of the pump waves electric field, $FP_\omega = (1 + F_\omega \sin(k_\omega l))^{-1}$ and $FP_{2\omega} = (1 + F_{2\omega} \sin(k_{2\omega} l))^{-1}$ are Airy functions describing Fabry-Perot interference for fundamental and second harmonic waves, $F_\omega = 4r_{1,\omega}r_{2,\omega}(1 + r_{1,\omega}r_{2,\omega})^{-2}$ and $F_{2\omega} = 4r_{1,2\omega}r_{2,2\omega}(1 + r_{1,2\omega}r_{2,2\omega})^{-2}$ are finesse of the Airy functions, $r_{1,\omega}$ and $r_{2,\omega}$ are amplitude reflection coefficients of the first and second boundaries of the nonlinear crystal for fundamental wave.

Analyzing formula (3), one can see, that output intensity is the product of 3 functions: sinc function, and two Airy functions describing Fabry-Perot interference. Airy functions in Equation (3) are responsible for the oscillations. They have different oscillating periods: $\tau_\omega = \lambda(n_\omega l(\alpha + \gamma_\omega))^{-1}$ for FP_ω and $\tau_{2\omega} = \lambda(2n_{2\omega} l(\alpha + \gamma_{2\omega}))^{-1}$ for $FP_{2\omega}$, where α is the thermal expansion coefficient of nonlinear crystal for a-axis direction (direction of light propagation). n_ω, γ_ω and $n_{2\omega}, \gamma_{2\omega}$ are extraordinary refractive index and thermo-optic coefficients for fundamental and second harmonic waves, respectively. Polarization of the fundamental and second harmonic waves are parallel to the c-axis of the crystal, and they propagate parallel to the a-axis. The input face of the crystal is polished and its intensity reflection coefficient is about 14% (Fresnel reflection). A dichroic mirror which is antireflective (AR) at 532nm and highly reflective (HR) at 1064nm is applied to the output surface of the crystal.

In Fig. 3 second harmonic intensity versus temperature, calculated with the formula 3 and experimental results are shown with solid line and markers, respectively. The experiment was conducted with a 1.5mm long PPLN plate, identical to the one used in the microchip laser. As a pump source, a CW, 1064nm $Nd^{3}+YVO_4$ single longitudinal mode laser was used.

Properties of the PPLN used in the calculations are shown in the Table 1.

It can be seen from the Fig. (3) that there is only one oscillation period, so only one Airy function is involved. The reason is the different finesse of the Fabry-Perot

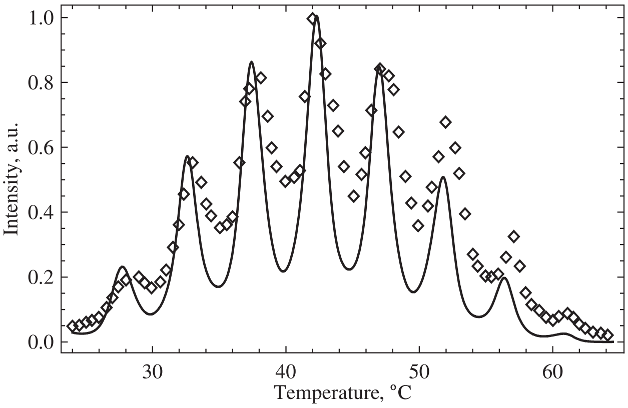


Fig. 3. Calculated and observed temperature dependence of single pass SHG in 1.5mm PPLN

Table 1. Properties of PPLN

Parameter	Value
Length	$l = 1.5mm$
Thermal expansion coefficient	$\alpha = 14.44 * 10^{-6}{}^{\circ}\mathrm{C}^{-1}$
n_e(44°C) at 1064nm	$n_1(44)$=2.148333
n_e(44°C) at 532nm	$n_2(44)$=2.224830
Domain grating period	$\Lambda = 6.94\mu$
Effective nonlinear susceptibility	$d_{eff} = 14pV/m$

interferometer for the fundamental and second harmonic wavelengths. Because of the AR properties of the output mirror, finesse at 532nm is negligible compared to the finesse at 1064nm, so only oscillations caused by multiple beam interference at 1064nm are present. The observed oscillation period for single pass SHG is $\tau_O = (5.1 \pm 0.5)°\mathrm{C}$, which is in a good agreement with the calculated value of $\tau_\omega = 4.8°\mathrm{C}$.

It can be seen from the Fig. (3) that theoretical calculations clearly predict oscillating behavior of the SHG intensity versus temperature.

4. Conclusion

Investigation of the temperature dependence of microchip output power shows oscillating behavior. Analysis of second harmonic generation in the plane parallel nonlinear crystal shows that oscillations are due to multiple beam interference in the nonlinear crystal. It is supposed that the oscillations in the microchip output power have the same origin. Detailed calculations for interference in the resonator of microchip laser will be conducted in the future.

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