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Second Harmonic Generation as a Method for Polarizing and Analyzing Laser Light

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Abstract. Second harmonic nonlinear crystals can be successfully used as light polarizers and analyzers. An extinction ratio (ER) of 6×10^{-9} for a system consisting of a Glan prism and KDP doubler is demonstrated. This nonlinear optical analyzer was used to test ER of calcite Glan air spaced prisms.

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Calcite is the most popular material for a polarizing prism [1, 2]. Typical extinction ratios (ER) for Glan laser air spaced polarizers are from 10^{-4} to 10^{-6} [1], depending on the quality. In some new kinds of experiments [3, 4] polarizers with better ER are required. To achieve this one has to follow instructions given by some authors [5, 6]: 1) by selection of a pair of best quality polarizers among some prisms; 2) by choosing the beam direction in the polarizer and analyzer; 3) by using a small-diameter beam; 4) by selection of the best place at the prism surface; 5) by increasing the distance between the analyzer and the photoreceiver, and finally; 6) by using diaphragms in order to block scattered ordinary rays. In this way ER of 10^{-10} was achieved [6].

Another way to obtain lower ER is to look for a new laser light polarizing method and devices. In this paper we show that second-harmonic-generating nonlinear crystals can be used successfully as sources of high-degree polarized light and as analyzers of polarized laser beams [7]. For these polarizers and analyzers ER of $(3–13) \times 10^{-8}$ and $(0.6–6) \times 10^{-8}$ were demonstrated, respectively.

1. Second-Harmonic Generation (SHG) as a Source of High-Degree Polarized Light

In negative uniaxial crystals without a center of symmetry two types of phase-matched (PM) processes are possible [8]:

Type I, when two ordinary incident waves produce an extraordinary SH wave. In the East European literature the notation $o_1 o_1 e_2$ is commonly ascribed to this type of SHG.

Type II, when one ordinary and one extraordinary fundamental waves produce again an extraordinary SH wave ($o_1 e_1 e_2$).

According to the nature of these processes the polarization of the extraordinary SH wave has to be ideal. Nevertheless, there are some reasons for spoiling the output beam polarization [9]: the depolarization of the SH beam due to a volume inhomogeneity in the crystal, the quality of the crystal output surface, thermo-induced tension divergence of the SH beam and self-induced rotation of the polarization plane. These factors are not typical only for the SH generators. They play the same depolarizing role in conventional polarizing prisms and other optical elements, and we shall not consider them in details.

Another major reason which influences the degree of the SH beam polarization is the generation of a SH ordinary wave (o_2), i.e. a wave with orthogonal polarization relatively to the PM SH wave (e_2). This SH ordinary wave is a result of nonemphasematched processes inside the crystal. For example, in negative uniaxial crystals, they are $o_1 o_1 o_2$, $o_1 e_1 o_2$, and $e_1 e_1 o_2$. Some of these processes can be forbidden because of crystal symmetry and orientation.

Further on we will limit the nonlinear media to the crystals of the KDP family ($\bar{4}2$ m point group). For this symmetry the $o_1 o_1 o_2$ non-PM process is forbidden for any orientation of the crystal. The non-PM processes

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Table 1. Calculated (only non phase matched processes are taken into account) and measured extinction ratios for KDP and CDA crystals used as nonlinear optical polarizers and analyzers

Non-linear crystal as	Crystal	PM process		Non-PM process			Crystal length [cm]	Extinction ratio, ξ	
		Inter-act. waves	β	Inter-act. waves	$d^{(2)}_{eff}$	l_{coh} [μm]		Calcul. $\xi \times 10^7$	Measured $\xi \times 10^7$
Polar-izer	Type-I KDP	$o_1o_1e_2$	0°	$o_1e_1o_2$	$d_{36}\sin\theta\sin2\varphi$	10.2	4	0.006	0.26; 0.8; 1.1; 1.3[a]
							0.3	1.1	3.2
	Type-I CDA	$o_1o_1e_2$	0°	$o_1e_1o_2$	$d_{36}\sin\theta\sin2\varphi$	9.4	2	0.02	0.9
	Type-II KDP	$o_1e_1e_2$	45°	$e_1e_1o_2$	$d_{36}\sin2\theta\cos2\varphi$	6.2	4	0.09	0.6
							0.64	3.7	1.9
Ana-lyzer	Type-I KDP	$o_1o_1e_2$	90°	$e_1e_1e_1$	$3d_{36}\cos^2\theta\sin\theta\sin2\varphi$	17	4	2.1	370
							0.3	340	70
	Type-II KDP	$o_1e_1e_2$	90°	$e_1e_1o_2$	$d_{36}\sin2\theta\cos2\varphi$	6.2	4	0.09	0.22
							0.64	3.7	1
		$o_1e_1e_2$	0°	–			4	0	0.06; 0.16; 0.3; 0.6[a]
							0.64	0	0.14

[a] The different values for the extinction ratio relate to the four investigated elements with one and the same orientation

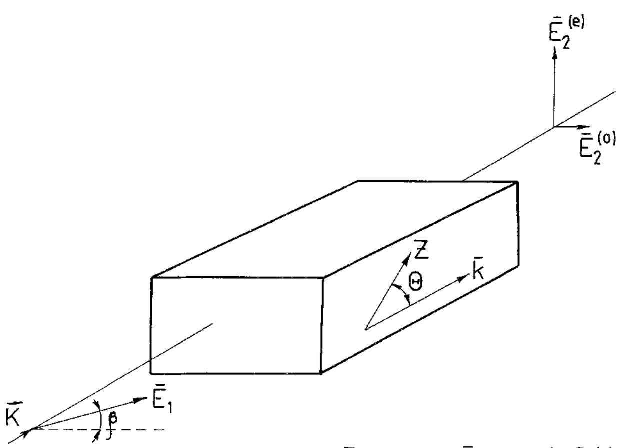

Fig. 1. Orientation of fundamental ($\bar{\mathbf{E}}_1$) and SH ($\bar{\mathbf{E}}_2$) electric-field vectors: $\bar{\mathbf{k}}$ is the wave vector coinciding with the direction of propagation, **Z** is the optical axis, ($\bar{\mathbf{k}}\bar{\mathbf{Z}}$) is the crystal main plane, θ is the angle of PM, β is the angle between the normal to the main plane and $\bar{\mathbf{E}}_1$ vector. $\bar{\mathbf{E}}_2^{(o)}$ is due to the non-PM processes and to the depolarization of $\mathbf{E}_2^{(e)}$

$o_1e_1o_2$ and $e_1e_1o_2$ are allowed for the Type I and Type II orientation of the KDP crystal, respectively. The intensity of this ordinary SH wave $I_2^{(o)}$ contributes to the depolarized component behind the exit face of the crystal. The ratio $I_2^{(o)}/I_2^{(e)}$ is the extinction ratio ξ of the generated SH beam. Using the expressions for PM and non-PM-SHG [8] we derive

a) for Type-I process

$$\xi=\frac{I_2^{(o)}}{I_2^{(e)}}=\gamma\left(\frac{2l_{coh}}{\pi L}\,\frac{d^{(2)}_{eff}(o_1e_1o_2)}{d^{(2)}_{eff}(o_1o_1e_2)}\right)^2; \tag{1}$$

b) for Type-II process

$$\xi=\frac{I_2^{(o)}}{I_2^{(e)}}=\left(\frac{2l_{coh}}{\pi L}\,\frac{d^{(2)}_{eff}(e_1e_1o_2}{d^{(2)}_{eff}(o_1e_1e_2)}\right)^2, \tag{2}$$

where l_{coh} is the coherent length for the non-PM process, L the crystal length, $d^{(2)}_{eff}$ the second-order nonlinear coefficient [10], and γ the extinction ratio $I_1^{(e)}/I_1^{(o)}$ for the fundamental beam inside the nonlinear crystal. Two factors have an influence on the value of the parameter γ. First, it is the nonperfect polarization of the incident beam and secondly the orientation of the polarization plane ($\bar{\mathbf{k}}\bar{\mathbf{E}}_1$) with respect to the crystal main plane ($\bar{\mathbf{k}}\bar{\mathbf{Z}}$). This is illustrated in Fig. 1. For our case, when we consider the SHG crystals as polarizers, the angle β has to be equal to 0° for the Type-I processes and 45° for the Type-II processes ($\gamma=1$). If $\beta=0°$, γ is equal to ER of the fundamental beam before entering the crystal.

Comparing (1 and 2) we see that using the Type-I process one can obtain an SH beam with lower ER because the coefficient γ can easily be made less than 10^{-2}. It is evident, that the longer the nonlinear crystal is the lower ER may be expected, but this decrease in ER will be limited by the depolarization effects discussed above. The calculated ER of the SH beam, generated in KDP and CDA crystals, are given in Table 1. In the calculation the value of γ was taken to be equal to the ER of the output beam of the laser used in the experiment (see Sect. 3).

2. SHG Crystal as an Analyzer of Laser Light

In this case the crystal has to be funed to PM direction and after that rotated around this direction (which coincides with the beam direction) until a minimum SH intensity is generated. At this orientation the

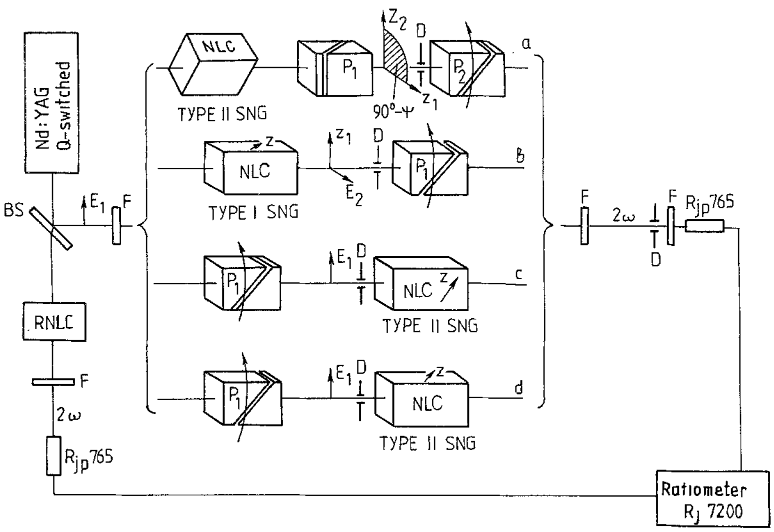

Fig. 2. Experimental arrangement for the ER measurements (BS: the beam splitter, F: filters, NLC: nonlinear crystals, RNLC: reference nonlinear crystal, $\mathbf{Z}_1, \mathbf{Z}_2$: optic axes of the calcite prisms, ψ: deviation of the angle between $\mathbf{Z}_1$ and $\mathbf{Z}_2$ from exact crossed orientation, $\mathbf{Z}$: optic axis of nonlinear crystals, P_1, P_2: Glan laser air spaced prisms PGL-10S (Lasermetric Inc.), D: diaphragms). *a* The scheme for measuring ER of a pair of Glan prisms; *b* Type-I SHG crystal as polarizer; *c*, *d* Type-II SHG crystal as analyzer (see text)

nonlinear crystal is very sensitive to any change in the input beam polarization. For example, for the Type I interaction, $o_1o_1e_2$, the crystal has to be simultaneously PM tuned and rotated such a way that the fundamental wave inside the crystal is "e" wave i.e. $\beta=90°$ (see Fig. 1). For the Type II interaction $(o_1e_1e_2)$ there are two values of the angle β at which the generated PM SH intensity is minimum 0° and 90°. Suppose, the incident beam has a perfect linear polarization. Then these two orientations are related to only "o" or only "e" fundamental waves propagating inside the SHG crystal. Both schemes can be used as analyzers of the change of the incident beam polarization. The question is: how low the ER of such analyzers can be?

Here again we have two main reasons limiting the ER of the system "Glan polarizer – SHG." First, it is the depolarization of the input beam on the crystal face and inside its volume. The depolarized component leads to the generation of PM SH signal and that increases ER.

The non-PM processes of SHG are the second limiting effect on the value of ER. We again restrict our consideration to crystals from $\bar{4}2$ m space point group. Three possible schemes were investigated:

– Type I, $\beta=90°$. Only one non-PM process is allowed – $e_1e_1e_2$. We derive $d_{\text{eff}}^{(2)}(e_1e_1e_2) = 3d_{36}\cos^2\vartheta\sin\vartheta\sin 2\varphi$. Its coherent length is relatively long and that leads to a high non-PM signal and to a rather bad ER;

– Type II, $\beta=90°$ (Fig. 2c). The non-PM process $e_1e_1o_2$ limits ER;

– Type II, $\beta=0°$ (Fig. 2d). This situation is very attractive, because there is no allowed non-PM process. ER will be limited only by the depolarization of the fundamental beam and we can expect very low value for it.

The estimated values of ER of the KDP doublers used as analyzers are listed in Table 1.

3. Experiment

The experimental arrangement for the ER measurement is shown in Fig. 2. The output radiation (10 mJ, 5 ns, 1 Hz) of the Q-switched Nd:YAG laser has a degree of polarization ~0.96. The beam diameter is 3 mm. The nonlinear crystals are standard commercial quality, some of them even homemade. The Glan laser air spaced prisms (Lasermetric, Inc.) are specified to have ER equal or better than 10^{-5}. The energy measurements were made at $\lambda=532$ nm with an Rj 7200 Ratiometer (Laser Precision Corp.) with two Rjp 765 photodiode probes.

The system was tested by measuring ER of a pair Glan prisms model PGL-10S (single side exit window) without AR coating (Fig. 2a).

Precautions must be provided to let the rejected "o" ray in the calcite prisms escape freely through the window. In Fig. 3a the transmittance dependence of the two polarizers on the deviation angle ψ from the exact crossed situation is plotted. The experimental curve or the extinction curve, as we will call it, fits well with the analytical expression:

$$I=I_{\min}+(I_0-I_{\min})\sin^2\psi\,, \tag{3}$$

where I_0 is the transmitted intensity when the prism axes are parallel.

Introducing $\xi=I_{\min}/I_0$ and for small deviation angle ψ we obtain

$$I=I_0(\xi+\psi^2)\,. \tag{4}$$

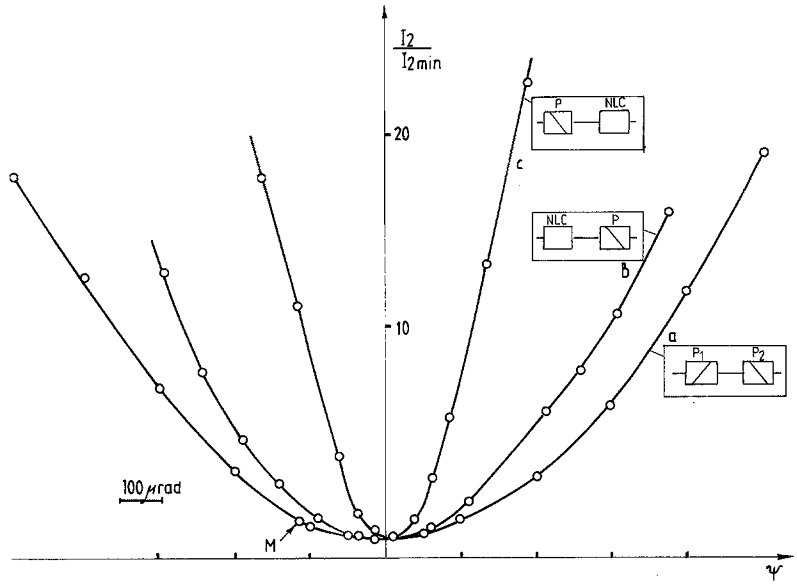

Fig. 3. Normalized SH light intensity around exact crossed orientation of a: *a* pair of Glan prisms; *b* Type-I KDP doubler and Glan prism; **c** Glan prism and Type-II KDP doubler. *M* is the "point of optimum geometry"

At the point M where $I_M = 2I_0\xi = 2I_{\min}$ and

$$\psi_M = \psi_{\text{opt}} = \sqrt{\xi} \tag{5}$$

the parameter $I^{-1}dI/d\psi$ has a maximum. This point is called "optimum polarization geometry" and is used to enhance greatly the polarimetric measurement sensitivity [3, 11, 12].

Using (5) from the experimental curve we determine $\xi = 4 \times 10^{-8}$ for the pair of Glan prisms. As shown further, the prisms are identical and so ER for the used single Glan laser polarizer at $\lambda = 532$ nm is 2×10^{-8}. Later we will take advantage of this method to find ER because there is no need to rely on the energy-meter's linearity for 10-order change of the input signals.

3.1. ER Measurement of the "SHG Crystal – Glan Prism" System

The nonlinear crystal (KDP or CDA) and the Glan prism were aligned, as shown in Fig. 2b. For the Type-I process four different KDP elements with length 40 mm were tested and for one of them $\xi = 2.6 \times 10^{-8}$ was obtained. Its extinction curve is shown in Fig. 3b. The measured ER for both processes (Types I and II) and for different crystal lengths are given in Table 1. Comparing the data we can see that the lowest ER is limited by the quality of the Glan prism. The fact that different elements have different ER shows that the depolarization on the exit face and in the volume is also important. ER for the shorter crystals are higher as it has been predicted by theory and it means that for short crystals the limiting factor is the non-PM process.

The main conclusion from this part of the experiment is that the SH beam generated in CDA and KDP crystals has a very high degree of polarization.

3.2. ER Measurement of the "Glan Prism – SHG Crystal" System

The KDP doubler is placed behind the Glan prism as it is shown in Fig. 2c, d. Each of the three schemes described in the theoretical part were examined. The results are given in Table 1. The lowest ER was measured for the Type-II interaction and $\beta = 0°$ when the fundamental beam inside the crystal is ordinary (Fig. 2d) and all non-PM processes are forbidden. A value of 6×10^{-9} was obtained for a selected part of the crystal face. The extinction curve is shown in Fig. 3c. At the point of optimum geometry ($I_2 = 2I_{2\,\min}$) we have 10% change of the signal for 1.4″ ($\sim 7 \times 10^{-6}$ rad) rotation of the polarization plane. For other entrance positions at the crystal face ER was within the range of $(0.6 \div 3) \times 10^{-8}$ [9]. We also noticed that for some of the investigated elements the change of the direction of the incident beam leads to changes of ER with a factor from 1 to 10. We would like also to note that at the point $I_2 = I_{2\,\min}$ (Fig. 3c), where the measured energy was about 3 pJ we registrated with confidence the PM tuning curve. Therefore, $I_{2\,\min}$ is the PM SH signal of the depolarized component of the pump beam which may arise either in the Glan prism or in the entrance part of the crystal. The fact that the measured ER of 4×10^{-8} for the pair Glan prisms PGL-10S is higher than that of the system "Glan prism – SH generator" can be explained by the fact that in the first case the Glan prism polarize at $\lambda = 532$ nm, and in the second case at $\lambda = 1064$ nm.

3.3. Use of SH Generation for Glan Prism Testing

As it was shown the Type-II SHG may be used as an analyzer with ER equal or better than 6×10^{-9}. We used these scheme (Fig. 2d) to compare four different

Table 2. Extinction ratios for different Glan laser air spaced prisms

No.	Model	Faces	Extinction ratio at $\lambda = 1064$ nm
1	PGL-10S	Uncoated	0.6×10^{-8}
2	PGL-10S	Uncoated	0.6×10^{-8}
3	PGL-8D	AR coated	6.0×10^{-8}
4a	PGL-15D	Uncoated	1.5×10^{-8}
4b	The same prism as 4a but turned end for end	Uncoated	14.0×10^{-8}

Glan laser prisms. The results are listed in Table 2. We see that the both prisms PGL-10S are identical. But we cannot determine ER of this kind of single prism because we don't know the exact ER for our frequency doubler as an analyzer. The measured ER for prisms N3 and N4 are higher than 6×10^{-9} and this numbers refer to ER of each prism correspondingly. We found that a change of the direction in the PGL-15D prism leads to a change in ER by a factor of 10. The same result was observed in [6].

4. Conclusion

We have shown that frequency-doubling nonlinear crystals can act as polarizers and analyzers of laser light. Extinction ratios of $10^{-7} \div 0.6 \times 10^{-8}$ were demonstrated. We suppose that using higher-quality nonlinear crystal better ER could be achieved.

The main advantages of the proposed polarizers and analyzers based on SHG are:

– ER lower than 10^{-7} are easily obtainable;

– crystals for SHG are easy to be produced than calcite prisms;

– crystals like $BaNaNb_2O_5$, $LiNbO_3$, $LiJO_3$, and KTP [13] could be used to obtain very low ER at wavelength above 3 μm, where calcite crystal has great absorption;

– in the schemes when the nonlinear crystal is used as an analyzer, the rotation of the fundamental-beam polarization plane is registered at its SH wavelength. Therefore, if we work in the infrared region we can use a more sensitive detection system;

– SH generation may be used as an etalon for linear polarized light and for testing other polarizing devices.

The major drawback of the SH polarizer and analyzer is its small angular field. A substantial increase of the angular field will take place when a nonlinear crystals with 90° phase matched angle are used.

Nonlinear, depending on polarization, processes such as sum- and difference-frequency generation, parametric amplification, four-frequency interactions and others can also be applied to polarize and analyze laser light.

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