Wide-band tunable and multiple noncritical phase-matchings in nonlinear optics

VICTOR I. ZADOROZHNII[1]*, NIKOLAI E. KORNIENKO[1], LJUDMILA I. KONOPALTSEVA[2] and ARINA M. SYTCHEVA[1]

[1]Kiev T. Shevchenko University, Department of Physics, Kiev, Ukraine
[2] Scientific-Research Engineering-Introduction Center of Priority Technologies on Optic Techniques, Kiev, Ukraine

The investigation and utilization of noncritical phase matchings in optical devices is a new focus for bulk and integrated nonlinear optics research. The use of vectorial group and multiple noncritical phase matchings for the sum – and difference – frequency generation in nonlinear crystals permits both to extend essentially the tuning range of the wide-band conversion to cover practically the entire transparency region of crystal and to attain the bandwidth of conversion of the order of 103 cm^{-1} in the mid-IR and the near-IR spectral regions. We discuss here a possible applications of noncritical phase matchings.

1. Introduction

There is an increasing interest in tunable nonlinear frequency and image converters as well as radiation sources for infrared spectroscopy, optical location, image visualization, creation of compact tunable coherent light sources [1-4]. The creation of the novel nonlinear materials and the improvement of properties of available pump-laser systems have led to a considerable progress in this field.

In our opinion, up to now insufficient attention has been given to the question of utilization of noncritical phase matchings in optical devices. In many cases the near-90° noncritical in angle phase matching (PM) and tangential PM (TPM) are exploited and merely some works deal with the collinear group PM, when along with the usual PM conditions $\omega_r = \omega_p \pm \omega_s$, $k_r(\omega_r,\theta_r) = k_p(\omega_p,\theta_p) \pm k_s(\omega_s,\theta_s)$ the equality of group velocities $v_s = v_r$ is required in collinear case at narrow-band pumping. The main drawback of pointed out PMs is the limited tuning range. The use of the noncritical vectorial group PM [5] extends the conversion possibilities, in particular, enables us to scan the wide-band group PM region along the transparency region of a crystal. In addition, the combination of the tangential and vectorial group PMs (double noncritical PM) makes it possible to obtain a simultaneous wide-band and wide-angle conversion of signals and images. By making use of different wavelengths of pumping, the regions of double and multiple [5] noncritical PMs can be displaced towards short or long wavelengths.

* corresponding author: Victor I. Zadorozhnii, Kiev T. Shevchenko University, Department of Physics, Kiev-17, 252601, Ukraine Tel.: +7(044)2664477, e-mail: Andreev% ipu.univ.kiev.ua @relay.ussr.eu.net

2. Vectorial noncritical phase matchings

We shall demonstrate the advantages in using vectorial noncritical PMs as an example of sum frequency generation $\omega_r = \omega_p + \omega_s$ in the uniaxial crystal $LiIO_3$ by nonlinear mixing of the pumping radiation of a ruby laser (λ_p = 694.3 nm) and the signal near-IR radiation. A schematic diagram of the wide-band converter is shown in Fig. 1. Calculated tuning curves are displayed in Fig. 2, where we have drawn angle ϕ between the directions of propagation of signal and pump waves

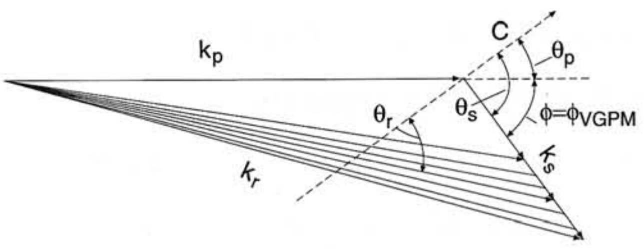

Fig. 1. Vector diagram of the wide-band conversion.

versus the signal wavelength (parameter: the internal angle of pump wave with respect to the optic axis C). It is assumed in demonstrated case that the setup for an infrared up-conversion allows only the -II interaction (eo-e),where the pump propagates as an extraordinary wave. Spectral tuning of the PM is attained by varying the geometry of the interaction, tuning of the pump wavelength (see Fig. 4) or by varying the temperature of a crystal. The well known conditions of noncritical in angle up-conversion (the tangential PM conditions) are satisfied in the vicinity of left and right extremity of the closed PM curves. The touch point of a PM curve with the abscissa axis corresponds to the collinear group PM. The conditions of noncritical in frequency up-conversion are fulfilled in the vicinity of upper and lower extreme points of the closed curves (along the curve of the noncritical vectorial group PM (VGPM) shown by dashed line in Fig. 2). At such geometry of the interaction, the VGPM condition is fulfilled when

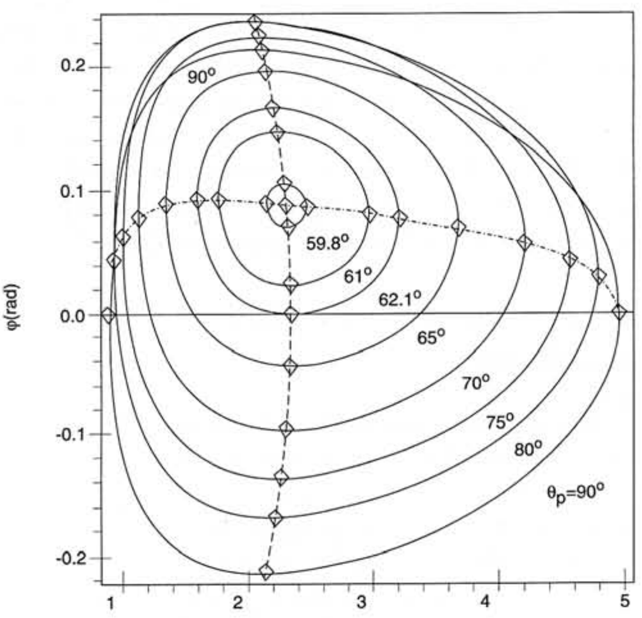

Fig. 2. Typical phase-matching curves of the $LiIO_3$ crystal illustrating noncritical (eo-e) PMs.

the projections v_r and v_s onto a direction $\mathbf{k}_s/k_s$ equals. The physical sense of this condition is to compensate the group velocities mismatch due to the interaction geometry and crystal anisotropy. There is significant advantage in using such PM because of the complete utilizing of the signal radiation in nonlinear-optic frequency conversion.

In general, the more favorable conditions for wide-band conversion take place along the VGPM-curve for a collimated wide-band signal radiation. However there are the regions along this curve where occur noncritical PMs of a more higher multiplicity. For example, in the vicinity of the intersection point of the VGPM and tangential PM (dash-dote curve) curves it realizes a double noncriticality (DNPM) both in frequency and direction of signal radiation propagation, where the absolute magnitudes of the group velocities v_r and v_s are equal and their directions are the same. The fact of the existence of such a degenerate point in the PM curve of the crystals has been discovered theoretically in [5] as well as noted in experiments in some crystals (by Midwinter and Warner in $LiNbO_3$ and also in the BBO crystal [6]). There also exist other noncritical multiple PMs of great practical interest. For example, there are double noncritical PMs in the vicinity of the left and right extreme points of the PM surface shown in Fig. 2, where $\delta\omega_s/\delta\omega_p = \delta\omega_s/\delta\phi = 0$. In this case the conversion process is noncritical in the divergence both pumping and signal radiation, that is a generalization of the scheme of tangential PM used by Warner and Midwinter. In the upper and lower points of PM surface $\delta\phi/\delta\omega_p = \delta\phi/\delta\omega_s = 0$ and the vectorial scheme is not sensitive both in monochromaticity of the signal radiation and in variations of pump direction. Taking into account that at $|\phi| \approx \phi_{max}$ ($\phi \in \phi_{VGPM}$) while the θ_p changes, the direction of k_s will vary too, this PM is conditionally of θ_s and $\mathbf{Q}_p$. When using the cylindrical focusing of pump in the principal plane this PM can be utilized to convert wide-band IR images. True TNPM (for example, in ω_r, ϕ, and θ_p) will be achieved at the specific pump frequency, when the PM surface contracts into a small region (in the limit into a point at $\theta_p = 90°$, $\phi = 0$). In this special case the 6 DNPM regions join into one common region and make up the TNPM region.

The software package has been developed to compute a frequency-angular spectrum structure of the nonlinear-optic converter and it was used to investigate the conversion characteristics in a line of uniaxial and biaxial crystals with transparency range of 0.3 – 20 μm ($LiIO_3$, $LiNbO_3$, KTP, RTP, $AgGaS_2$, $HgGa_2S_4$, CdSe and the others). The typical calcu-

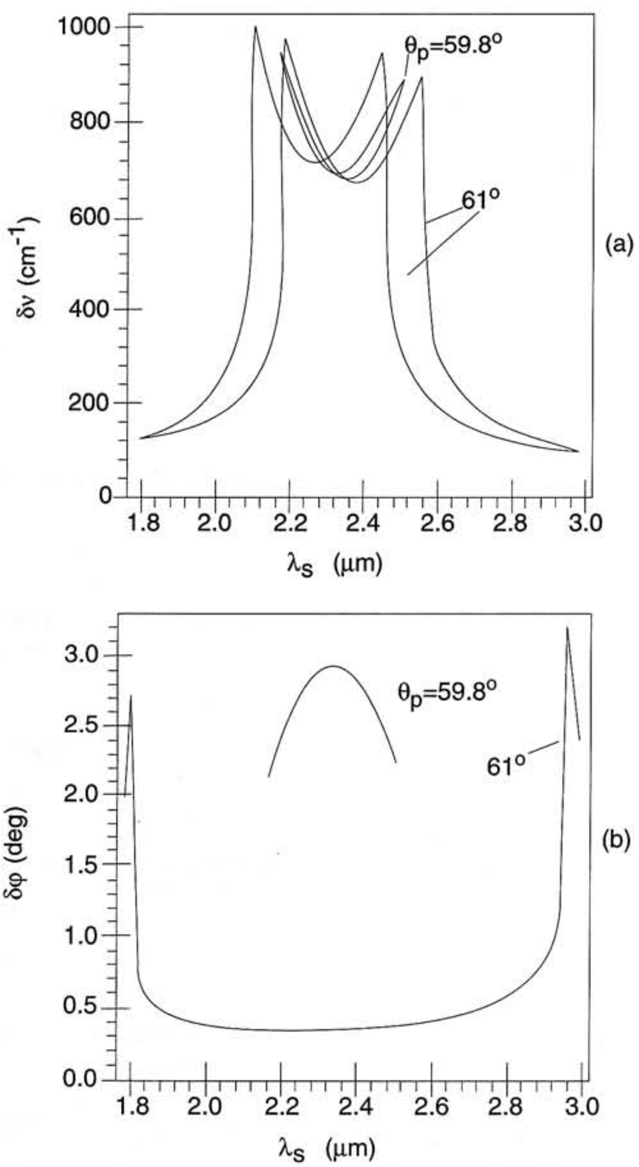

Fig. 3. Spectral bandwidths (a) and acceptance angles (b) at the half-intensity level of generated radiation for noncritical (eo-e) PM at λ_p=694.3 nm in $LiIO_3$ (L=4 mm) near the DNPM region.

lated dependences of spectral bandwidth $\delta\nu$ and angular width (acceptance angle) $\delta\phi$ on λ_s are shown in Figures 3(a) and 3(b), respectively. From shown figures it is seen that the use of the pointed out noncriticalities in PM allows us to improve the characteristics of converters, in particular, increase the magnitude of the conversion band and acceptance angle (up to $2 \cdot 10^3$ cm^{-1} and 5 degrees in the separate crystals).

The possibility of scanning the VGPM region at the concordant change in angles θ_p and ϕ as well as at the change in pumping wavelength is demonstrated in Fig. 4 by examples of the near-IR and mid-IR crystals. One can see that the scanning range cover the considerable part of the transparency region of the nonlinear crystals. In most cases when the longer wavelength pumping is used, the VGPM and DNPM regions shift towards short wavelength region and the tuning range extends at ω_p = const. As seen in Fig. 4, when the two (or three)-frequency pumping is used (for example, 2 or 3 wavelength of Nd:YAG laser), the conversion bands at VGPM in the same crystal may touch with each other and form the single wide conversion band. The same extension of the band can be attained when using a single-frequency pump laser and a composite nonlinear element consisting of the two or more specially selected and oriented crystals. The use of converters of 6-12 mm in length enables us to attain a band of conversion of 4 μm around 10 μm and cover the atmospheric window.

3. Conclusion

In summary, we have discussed the new opportunities arisen due to noncritical PMs utilization. The use of the vectorial group and multiple phase-matchings in nonlinear bulk (as well as in waveguide) frequency converters is an attractive way to extend the tuning range, considerably increase the bandwidth and acceptance angle of conversion, and improve the characteristics of the available light sources and converters taking advantage of the high stability of the devices for disturbances.

For further applications some directions are interesting. The first is the use of VGPM to create new coherent radiation sources and frequency converters of femtosecond pulses. The second direction is the conversion of wide-band impulse (pico- and nanosecond duration) or continuous radiation from the IR and UV to the visible spectral range. In this case the wide-band spectrum of signal radiation can be related to the homogeneous (or the other nature) widening in solids or to the various vibration-rotation states in gaseous media. The third direction is the use of VGPM in optical parametric oscillators to generate narrow-band tunable radiation using the wide-band pump radiation. Noncritical in angles PMs allow to convert divergent radiation into narrow-band beamed one and vice versa. At last, double noncritical PMs allow to visualize the wide-band IR images.

Using VGPM and multiple PMs the new spectroscopy methods can be developed, which make possible to register the vibration and electron spectra of short-lived radicals or intermediate products of chemical reactions.

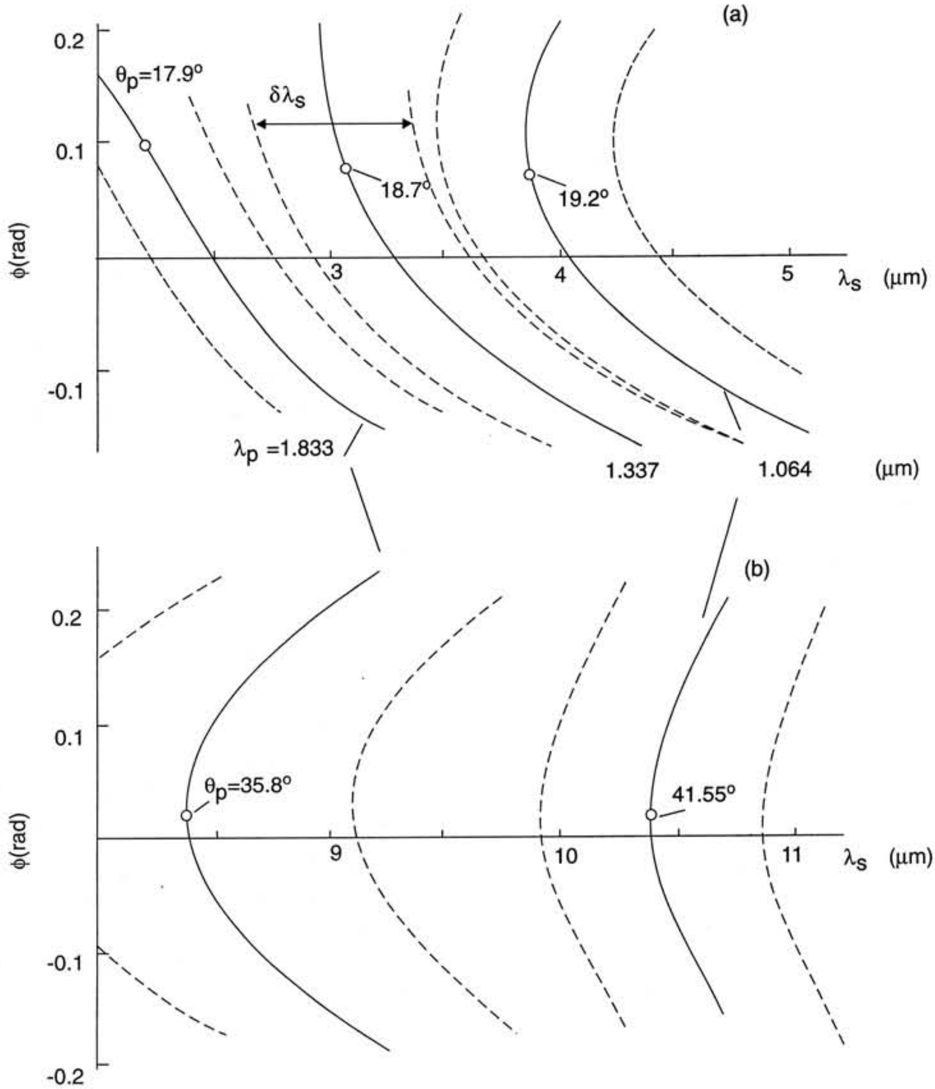

Fig. 4. Possibilities of scanning the VGPM (solid lines) and DNPM (cricles) region in $LiIO_3$ (a) and $HgGa_2S_4$ (b) (interaction oo-e, L=4 mm).

4. Acknowledgments

This work was financed in the frame work of SCSI of Ukraine on the program 04.01.05.

References

1. R. Laenen, K. Wolfrum, A. Seilmeier, A. Laubereau: *Parametric generation of femtosecond and picosecond pulses for spectroscopic applications.*, J. Opt. Soc. Am. B, **10** (1993) 2151.
2. Y. Shuto: *Normal-mode analysis of noncollinearly phase-matched second-harmonic generation in poled-polymer thin-film waveguides.*, J. Opt. Soc. Am. B, **10** (1993) 1221.
3. S. B. Karamyshev, R. D. Mukhmedyarov, R. Sh. Usmanov: *Wide-band two-stage up-conversion of IR radiation.*, J. Appl. Spectroscopy, **51** (1990) 495.
4. A. Nebel, C. Fallnich, R. Beigang, R. Wallenstein: *Noncritically phase-matched continuous-wave mode-locked singly resonant optical parametric oscillator synchronously pumped by Ti:sapphire laser.*, J. Opt. Soc. Am. B, **10** (1993) 2195.
5. S. G. Dolinchuk, N. E. Kornienko, V.I. Zadorozhnii: *Noncritical vectorial phase matchings in nonlinear optics of crystals and infrared up-conversion.*, Infrared Phys. Technol.., **35** (1994) 881.
6. P. E. Powers, R. J. Ellingson, W. S. Pelouch, C. L. Tang: *Recent advances of the Ti:sapphire-pumped high-repetition-rate femtosecond optical parametric oscillator.*, J. Opt. Soc. Am. B, **10** (1993) 2162.

