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3. I. C. Khoo, "Nonlinear optics of liquid crystals," in "Progress in Optics," Vol. XXVI ed. E. Wolf (North Holland, Amsterdam, 1988).

12:15pm

CThJ7 Methods of achieving phase conjugation in local response media

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Over the last decade, particular attention has been paid in nonlinear optics to theory and use of phase conjugation in photorefractive materials. The main reason for such interest is that their nonlinear response enables one to achieve amplification in two-beam interaction and hence create a greater number of phase-conjugation schemes.[1] However, it must be confessed that photorefractive media possess essential shortcomings: they are too expensive, too fragile, and cannot work in IR band and withstand large powers. Meanwhile there is a great amount of very simple and widespread capability in nature media with local response (for example, with heat mechanism of nonlinearity). But achieving passive phase conjugation in such media has intuitively seemed to be hindered or even impossible because the energy exchange between two beams is forbidden in local media. And, indeed, careful analysis shows that generation of phase-conjugatd waves in schemes of double phase conjugation or ring mirror is impossible. To conquer this difficulty it has been proposed that an amplifier be introduced into the feedback circuit to compensate the absense of nonlinear amplification in the ring mirror.[2] Yet there is another difficulty which hinders achievement of phase-conjugated wave generation. To explain that, let us consider two nonlinear media with the local mechanism of nonlinearity. Beam A_2 and some seeding field A_3 write phase grating σn_1 in medium 1 (Fig. 1). The second beam A_1 after its scattering on this grating creates the field A_4 whose phase is shifted by $\pi/2$ with respect to that of A_1: $A_4 \sim i\, A_1$. Then field A_1 and A_4 interacting in medium 2 write the grating $\sigma n_2 \sim \sigma n_1 \cdot \exp(i\phi_1 - \pi/2)$, where ϕ_1 phase difference of beams A_1 and A_4 propagating along paths L_1 and L_2, respectively. Beam A_2 scattering on grating σn_2 gives field A_3 phase shifted by $-\pi/2$ with respect to A_2: $A_3 \sim -i\, A_2$. Beams A_2 and A_3 interfere in medium 1 again and give an additional part to grating $\sigma n_1 : \Delta n_1 \sim \sigma n_1 \exp(i(\phi_1 - \phi_2) - \pi)$ with ϕ_2 phase difference between A_3 and A_2 propagating along paths L_1 and L_2, respectively. If $\phi_1 - \phi_2 = 0$ (as usually takes place) the feedback is negative and even introduction of an amplifier will not result in onset of generation. Analysing this scheme more carefully one can show that the threshold condition is $M \sin \phi/2 > 1$ where $M = gIl$, g is the local increment of nonlinearity, I is the intensity of input waves, l is the length of media, and $\phi = \phi_1 - \phi_2$ is the nonmutual phase shift. The threshold is minimized if $\phi = \pi + 2\pi n$. Obviously it is impossible to achieve phase conjugation without any extra artificial method. One particular possibility was treated in our previous papers.[3,4] where the generation of phase-conjugated waves was achieved due to the frequency difference of input waves A_1 and A_2 and difference of lengths L_1 and L_2. But it is just one example of the general principle of nonmutual phase shift. This principle declares that the formal character of medium response may be changed by division of the medium and introduction of a nonmutual phase shift of waves propagating in opposite directions. Other examples of its applications are described below.

If the nonlinear medium has a response independent of the polarizaiton of the interacting beams it would be best to use beams A_1 and A_2 with mutual orthogonal linear polarizations. It could then be possible to take a birefringent material (plate $\lambda/2$) as a phase element 3 (Fig. 1). Nonlinear amplification is achieved due to the frequency shift of generated waves.

If a nonlinear medium is not isotropic with respect to beam polarizations it is necessary to provide the same polarization of all the interacting beams and to attain their phase difference. It can be achieved if we place a birefringent material between two Faraday rotators 4,5 which rotate polarization by $\pi/4$ (Fig. 2). The magnetic fields in Faraday cells should be in opposite directions. The axis of ordinary polarization of birefringent material should be oriented at $\pi/4$ with respect to polarizations of A_1 and A_2.

The principle in point may be useful for other PC devices. Let us consider a ring passive mirror (Fig. 3). One can show that in this scheme the threshold condition is $M \sin \phi > 1$ and optimal regime is achieved when $\phi = \pi/2$. This condition may be satisfied if quarter plate 3 is placed behind Faraday cell 2 which rotate polarization by $\pi/4$. Then after passing feedback circuit waves get nonmutual phase shift π in the Faraday cell and $-\pi/2$ in the place $\lambda/4$. Thus the required phase shift ($\pi/2$ is achieved.

In conclusion, we express confidence that the described principle will lead not only to expanding the class of media used in well known devices but also will lead to interesting and unexpected schematic solutions and phenomena and open new realms of investigations. We would like all who engage in phase conjugation to pay attention to these promising possibilities.

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2. I. M. Beldyugin *et al.*, Kvantovaya Elektron. **11**, 887 (1984).
3. I. M. Beldyugin *et al.*, in *Conference on Lasers and Electro-Optics*, Vol. 12, OSA Technical Digest Series, (Optical Society of America, Washington, D.C., 1992).
4. I. M. Beldyugin *et al.*, Kvantovaya Elektron. **18**, 1150 (1991).

Thursday MORNING
May 6, 1993 CThK
Convention Center Room 310

10:30am OPOs: Novel Materials

Stephen C. Rand, *University of Michigan, Presider*

10:30am

CThK1 Optical parametric frequency conversion properties of KTiOAsO4 (KTA)

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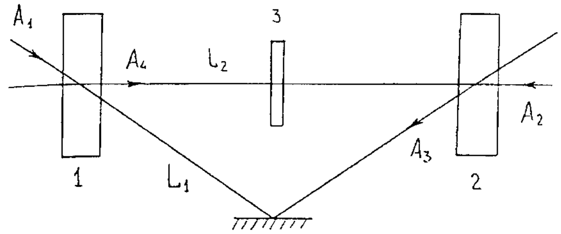
Optical parametric oscillators (OPO) have established themselves as efficient, reliable, solid-state sources of tunable radiation that can operate in many regions of the spectrum where no viable laser sources exist. One such region, 3 – 5 μm, is particularly interesting for many spectroscopic and remote sensing applications. Using other established nonlinear optical materials such as BBO, KTP, LBO, lithium niobate, $AgGaS_2$, $AgGaSe_2$, and $ZnGeP_2$ to obtain light in this spectral region has proved impractical because of their lack of transmission and/or their low optical damage thresholds. Recently, large single domain crystals of potassium titanyl arsenate ($KTiOAsO_4$, KTA) have been grown.[1] This material is similar in many ways to its isomorph, the more well-known material, KTP, but has better transmission at infrared wavelengths (IR cutoff is ~5 μm). Here, experimental results are presented demonstrating the utility of KTA for generating tunable radiation in the infrared.

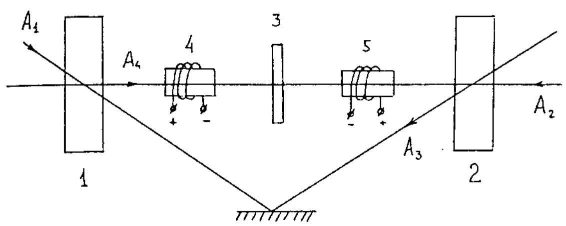
Inclusion-free KTA crystal boules of up to $35 \times 31 \times 58$ mm^3 were grown by flux techniques using either the tungstate or pure arsenate flux similar to what has been previously reported.[2] To promote the formation of single domain crystal, a trivalent oxide of In (dopant level ~0.2 wt.%) was added into the melt, and the crystal growth was carried out below the Curie temperature of KTA ($t_c \sim 880°C$). From these boules three single-domain KTA crystals were fabricated suitable for optical parametric frequency conversion. Crystal 1 was cut at $\theta = 49°$, $\phi = 0°$ (*x-z* plane) and was $4.8 \times 3 \times 8.3$ mm^3 (*x-z, y*, length) in size. Crystals 2 and 3 were both cut at $\theta = 90°$, $\phi = 0°$ (*x*-axis). Crystal 2 was $4 \times 3 \times 10$ mm^3 (*y, z*, length), whereas Crystal 3 was $5.9 \times 6.8 \times 10.7$ mm^3 (*y, z*, length). Crystal 2 was grown using a $K_5As_3O_{10}$ flux whereas Crystals 1 and 3 were grown from the tungstate flux.[2] To varying degrees, refractive index striations were observed in all three crystals.

The OPO tuning curves for KTA pumped at 1.064 μm and 532 nm were measured by observing sum frequency generation in the KTA of the signal and idler waves from the output of a KTP OPO pumped at the above two wavelengths. The KTP signal wavelength was measured with a monochromator,

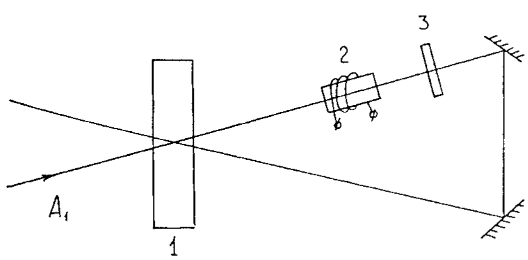
Thursday 6th



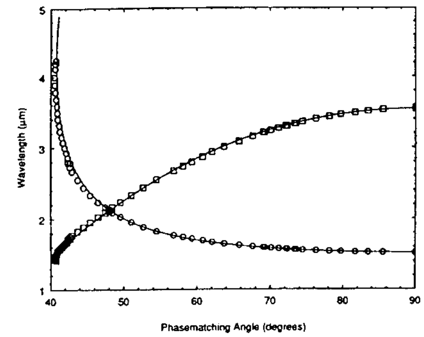
CThJ7 Fig. 1. Scheme of double phase conjugation in the case when local nonlinearity of media depends on polarization.



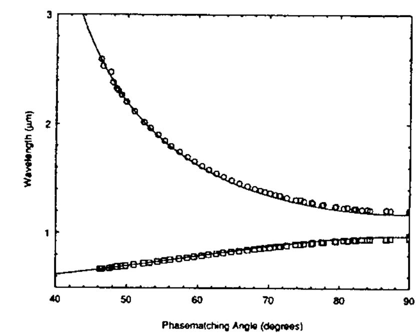
CThJ7 Fig. 2. Scheme of double phase conjugation in the case when from local nonlinearity of media is independent polarization.



CThJ7 Fig. 3. Scheme of ring passive mirror based on local nonlinearity.



CThK1 Fig. 1. Experimentally measured optical parametric tuning curves for KTA pumped by 1.064-µm radiation for angle tuning in the x-z plane ($\phi = 0°$). Solid lines are calculated tuning curves obtained from Sellmeier equations given in the text.



CThK1 Fig. 2. Same as Fig. 1 except that the pump wavelength is 532 nm.

CThK1 Table 1. OPO Parameters for noncritical phase matching along the x-axis for KTA and KTP.

	KTA #2	KTA #3	KTP
Crystal Length (mm)	10	10.7	15
Wavelength signal	1.520	1.524	1.572
(µm) idler	3.547	3.525	3.292
Threshold Energy (mJ)	21	23	10
Threshold Intensity (MW/cm^2)	210	230	100
Nonlinear Drive (C^2L^2I) @ threshold	2.4	3.0	2.5
Slope Efficiency (%)	38	40	53

and the KTA was angle tuned on a calibrated rotation mount to give the largest sum frequency output. The results are shown in Figs. 1 and 2. A single smooth phase matching peak was observed for each of the data points in Figs. 1 and 2 indicating no evidence of multidomaining in the KTA crystals. The solid lines in the figures are the calculated tuning curves based on the following Sellmeier equations:

(λ in microns)

$$n_X^2 = 2.1106 + 1.0318/[1-(0.2109/\lambda)^2] - 0.0090\,\lambda^2$$

$$n_y^2 = 2.3889 + 0.7790/[1-(0.2378/\lambda)^2] - 0.0105\,\lambda^2$$

$$n_z^2 = 2.3472 + 1.1011/[1-(0.2402/\lambda)^2] - 0.0141\lambda^2$$

These Sellmeier equations are obtained from a best fit of the refractive index data measured with undoped KTA in the spectral region of 0.45–1.5 μm.[1] The infrared coefficient (the coefficient of the last term in each equation) was then adjusted to best fit the OPO tuning curve data from this study.

Crystals 2 and 3 were also used in an OPO configuration to measure oscillation thresholds relative to KTP when pumped by 1.064 μm radiation. The OPO configuration was the standard two mirror flat-flat cavity. The input coupler was highly reflecting (R > 98%) at the signal wavelength and highly transmitting (R ~ 10%) at both the pump and idler wavelengths. The output coupler had reflectivities of R = 98% at the pump wavelength, R = 10% at the signal wavelength and R ~ 10% at the idler wavelength. The KTP crystal used as a comparison is cut the same (q = 90°, ϕ = 0°) but is 15 mm in length. These results are summarized in Table 1. The lower threshold energy and intensity of KTP is mainly caused by the longer length of the KTP crystal as all crystals have similar threshold nonlinear drives. The KTA #2 crystal was pumped up to 2.6 times above threshold obtaining a total conversion efficiency (signal + idler) of ~20%. Pumping was limited by damage to the input coupler. This OPO was not optimized in any way; it only shows that KTA operates similarly to KTP as an OPO material.

In summary, the optical parametric phase matching behavior of the new material KTA has been experimentally measured for pump wavelengths of 532 nm and 1.064 μm. Some OPO oscillation threshold and conversion efficiency data has been obtained for comparison of this material to KTP. KTA is a very promising material for optical parametric frequency generation in the important 3 – 5 μm region of the spectrum.

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1. L. K. Cheng, L. T. Cheng, J. D. Bierlein, F. Z. Zumsteg, A. A. Ballman, submitted for publication in Appl. Phys. Lett., Sept. 1992.
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Thursday 6th

10:45am

CThK2 High-repetition-rate femtosecond optical parametric oscillator using In:KTA

P. E. Powers, W. S. Pelouch, S. Ramakrishna, C. L. Tang, K. L. Cheng*

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The recent development of externally pumped high-repetition-rate fs OPOs using $KTiOPO_4$ (KTP) has opened the possibility for a broadly tunable high-repetition-rate fs source.[1,2] The potential tuning range of the fs KTP OPO is ~ .95–4 μm with an absorption band around 3.5 μm. To tune out beyond this range will require using other crystals. The nonlinear crystal In:KTA is such a crystal with a transparency range extending out to 5.3 μm with no absorption in the 3.5 μm region. The tuning curve for the In:KTA OPO pumped by a 850-nm Ti:sapphire pump is shown in Fig. 1. In:KTA also has a relatively large d_{eff}, and when pumped with a Ti:sapphire laser it has a small inverse group velocity mismatch between the pump and signal (less than 60 fs/mm over the whole tuning range) allowing for the generation of fs pulses. This summary presents the operating characteristics of the first fs OPO using In:KTA.

We first performed a general survey of the operation of the In:KTA OPO using a cavity without group velocity dispersion compensation as illustrated in Fig. 2. The In:KTA crystal is cut at θ = 50° and ϕ = 0° for type II phase matching ($o \rightarrow e + o$) and is AR coated from 1.3 to 1.6 μm. The crystal is aligned for oscillation in the x-z plane. The two r = 10 cm OPO cavity mirrors are aligned such that the Poynting vector of the signal wave walks onto the Poynting vector of the pump wave. The Ti:sapphire pump is focused onto the crystal with an r = 15cm mirror. With one mirror set we tune from 1.3 to 1.45 μm in the signal branch and from 2.04 to 1.75 μm in the idler branch. Without dispersion compensation, chirped pulses are produced over this wavelength range. However, unchirped pulses are possible without intracavity dispersion compensation. With 89-fs pump pulses at 790 nm, we produce 175-fs unchirped signal pulses at 1.435 μm as shown in Fig. 3. With intracavity dispersion compensation and a thinner crystal we expect to generate unchirped pulses as short as the pump pulses.

In conclusion we have demonstrated, we believe, the first operation of a high-repetition-rate optical parametric oscillator based on the nonlinear crystal In:KTA. We have shown that fs In:KTA OPO can generate unchirped pulses and can potentially reach the important 4–5 μm region.

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1. W. S. Pelouch, P. E.Powers, C. L. Tang, Opt. Lett. **17**, 1070 (1992).
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11:00am Invited

CThK3 Broadly tunable infra parametric oscillatior an organic crystal

D. Josse, S. X. Dou, J. Zyss

Department d'Electronique Quantique e Moleculaire, CNET, Laboratoire de Bag 196 Avenue Henri Ravera, BP 107, 92225-Bagneux Cedex, France

After over a decade of investigations at the engineering of highly efficient ear molecules and crystals as well a development of adequate crystal techniques, an important milestone h reached based on the unique features Nitrophenyl)-L-prolinol (NPP). N highly efficient organic nonlinear crystal displaying quasioptimal mo $P2_1$, stacking of the molecular units t the optimization of the d_{21} coefficier most efficient second-harmonic and s quency generation phase matching (P figuration corresponds to a type I int scheme in the XZ principal dielectric the crystal. An optical parametric o (OPO)[5] using NPP based on this PM uration has been demonstrated w pump wave polarized along the Y p axis of the crystal while the signal ar waves are polarized in the XZ plane.

The crystal has been grown from lowing a method recently develo POM (3-melhyl-4-nitropyridine-1- and the crystalline sample used in th iment exhibits two polished faces pa the XY principal plane. The physical sions of the crystal are 11.0 × 5.0 × 1 with 1.9 mm along Z. The pump b 0.5927 μm is obtained by type II nonc sum-frequency generation in KTP c and 1.338 μm Nd:YAG lasers. The 1.0 is Q-switched with an output pulse d of 15 ns while the 1.338 μm laser is mode-locked, leading to a train o pulses of 1 ns duration. The two las synchronized so as to generate only gle 1 ns-duration pulse in the KTP cr a 5-Hz repetition rate. The noncollima low pump beam is directed onto th cavity with a beam radius ω_{0p} of 0.5 the NPP sample.

A tunable wavelength range fron 1.7 μm has been obtained by internal of 3.6° (external angle of 7.3°). With t nar mirrors of higher reflectivities a wavelength. (See Fig. 1.)

Using the same front mirror but a rear mirror, a total conversion effici 4.7% for an incident pump pulse en the crystal of 0.41 mJ has been reac maximal signal (idler) energy per pul μJ (8 μJ) is reached at 0.955 μm (1.28 θ = 11.5°, the oscillation threshold ene the output at fixed pump energy ha measured at different L as shown in I

High nonlinearity is crucial for C eration at the present time scale of th The dependence of the oscillation th energy on the effective nonlinear co in a singly resonant OPO is plotted i the estimation being based on a nor ing hypothetical crystal with the sam tive indices as NPP. A precise detern method of the oscillation threshold, passing walk-off and Gaussian bea