Conference on Lasers and Electro-Optics

1993 Technical Digest Series Volume 11

Postconference Edition

Summaries of papers presented at the Conference on Lasers and Electro-Optics May 2–7, 1993 Baltimore, Maryland

19941214 034

Sponsored by
Optical Society of America
IEEE/Lasers and Electro-Optics Society

in cooperation with
Quantum Electronics Division of the European Physical Society
Japanese Quantum Electronics Joint Group

Optical Society of America
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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. 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 nonlinearity 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-conjugated 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 absence of nonlinear amplification in the ring mirror. 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 $\sigma_1$ in medium 1 (Fig. 1). The second beam $A_2$ after its scattering on this grating creates the field $A_2''$ whose phase is shifted by $\pi/2$ with respect to that of $A_2$, $A_2'' \sim A_1$. Then field $A_1$ and $A_2''$ interacting in medium 2 write the grating $\sigma_2'' = -\sigma_1$, $\exp(i\phi_2 = -\pi/2)$, where $\phi_2$ phase difference of beams $A_1$ and $A_2''$ propagating along paths $L_1$ and $L_2$, respectively. Beam $A_2''$ scattering on grating $\sigma_2''$ gives field $A_3''$ phase shifted by $\pi/2$ with respect to $A_2$: $A_3'' \sim -iA_2$. Beam $A_3$ and $A_3''$ interfere in medium 1 again and give an additional part to grating $\sigma_3$: $\sigma_3 = -\sigma_1 \exp(i(\phi_1 - \phi_2) = -\pi)$ with $\phi_2$ phase difference of beams $A_2$ 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 $M = gll'$, $l'$ 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 $\phi = -\pi - 2m\pi$. Obviously it is impossible to achieve phase conjugation without any external artificial method. One particular possibility was treated in our previous papers, 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 polarization 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 $x/2$) 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 $\pi$ in the Faraday cell and $\pi/2$ in the place $L_3$. 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.

CThK1 Fig. 1. Exponentially measured optical parametric tuning curves for KTA pumped by 1.064-μm radiation for angle tuning in the x-z plane (θ = 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.

<table>
<thead>
<tr>
<th></th>
<th>KTA #2</th>
<th>KTA #3</th>
<th>KTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Length (mm)</td>
<td>10</td>
<td>10.7</td>
<td>15</td>
</tr>
<tr>
<td>Wavelength signal (μm)</td>
<td>1.520</td>
<td>1.524</td>
<td>1.572</td>
</tr>
<tr>
<td>Wavelength idler (μm)</td>
<td>3.547</td>
<td>3.525</td>
<td>3.292</td>
</tr>
<tr>
<td>Threshold Energy (mJ)</td>
<td>21</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>Threshold Intensity (MW/cm²)</td>
<td>210</td>
<td>230</td>
<td>100</td>
</tr>
<tr>
<td>Nonlinear Drive (C²L²) @ threshold</td>
<td>2.4</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Slope Efficiency (%)</td>
<td>28</td>
<td>40</td>
<td>53</td>
</tr>
</tbody>
</table>
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 the monomodal nature of the tuning in the KTA crystals. The solid lines in the figures are the calculated tuning curves based on the following Sellmeier equations:

\[
\begin{align*}
\eta_x^2 & = 2.1106 + 0.0131/[(1-0.2109/\lambda^2)] - 0.0090 \lambda^2 \\
\eta_y^2 & = 2.3889 + 0.7790/[(1-0.2378/\lambda^2)] - 0.0105 \lambda^2 \\
\eta_z^2 & = 2.3472 + 1.0111/[(1-0.2402/\lambda^2)] - 0.0141 \lambda^2
\end{align*}
\]

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. The infrared coefficient (the coefficient of the last term in each equation) was then adjusted to best fit the OPO tuning data from the crystals.

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 > 90%) 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 (α = 90°, β = 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 coefficients. 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.

**References**