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Multiple-mode phase matching in a single-crystal lithium niobate waveguide for three-wave mixing

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Developing natural “free space” frequency upconversion is essential for photonic integrated circuits. In a single-crystal lithium niobate thin film planar waveguide of less than 1 μm thickness, we achieve type I and type II mode phase-matching conditions simultaneously for this thin film planar waveguide. Finally, by employing the mode phase matching of \( e \rightarrow e, o \rightarrow o, e \rightarrow o \) and type II SHG includes \( e \rightarrow o \rightarrow o \) and \( e + o \rightarrow e \). The spontaneous parametric downconversion (SPDC) was also analyzed by studying type II SHG at 1.55 μm for the \( e \rightarrow o \rightarrow o \) case.

During the three-wave mixing in LN, the energy and momentum conservation must be satisfied. They can be expressed by

\[
\omega_1 + \omega_2 = \omega_3, \\
\Delta \vec{k} = \vec{k}_3 - (\vec{k}_1 + \vec{k}_2),
\]

where \( \omega_i \) represent the frequency and wave vector, respectively. When \( \vec{k}_1 \) and \( \vec{k}_2 \) are equal, the three-wave mixing represents the SHG. The second-harmonic (SH) waves can be efficiently generated after satisfying the phase-matching condition \( \Delta \vec{k} = 0 \), in which the refractive indices of the fundamental wave (FW) \( n_1 \) and SH wave \( n_3 \) must be the same. Generally, the condition of \( n_1 = n_3 \) cannot be satisfied because of the intrinsic material dispersion.

A schematic diagram of LN on insulator (LNOI) is shown in Fig. 1(a); 1.9 μm silica is sandwiched by LN thin film and the LN substrate. Figure 1(b) illustrates the propagation path of guiding mode waves. \( n_i, n_c, \) and \( n_s \) represent the refractive indices of the thin film layer (guiding layer), air (cladding layer), and silica layer (substrate layer), respectively. \( h \) is the thickness of the guiding layer, which can be processed ranging from 300 to 900 nm. Figure 1(c) is the two different mode field distributions in the film with the thicknesses of 300 and 900 nm, respectively. The mode field distribution under different thicknesses has different areas, which is shown in Fig. 1(d). It represents the relationship between the mode size and the
thickness of the film, which is approximately linear. For the
guiding wave confined in the film, the larger the thick-
ness is, the smaller the mode field mismatch is, and the
higher the coupling efficiency is. It is worth noting that
we use Z-cut 5% MgO-doped LN thin film at 25°C. \(n_f\)
of LN satisfies the Sellmeier equation[22]\(^1\), and \(n_f\)
of silica is uniformly set as 1.45. Assuming that the wave propa-
gates along path ABCD in Fig. 1(b), the total horizontal
(Z axis direction) phase shift is:

\[
2k_0n_f \cos \theta \cdot h + \phi_{fc} + \phi_{fs}.
\]

Here, \(k_0\) represents the wave vector in a vacuum, \(\theta\)
represents the reflection angle, and \(\phi_{fc}\) and \(\phi_{fs}\) represent
the total reflection phase shift of point B and point C, respec-
tively. It should be noticed that the TE- and TM-polarized
definitions of \(\phi_{fc}\) and \(\phi_{fs}\) are different. They are given by

\[
\tan \frac{\phi_{fc}}{2} = -\frac{\sqrt{n_c^2 \sin^2 \theta - n_f^2}}{n_f \cos \theta}, \quad \text{TE – polarized,}
\]

\[
\cos \phi_{fc} = \frac{n_f \cos \theta}{\sqrt{n_c^2 \sin^2 \theta - n_f^2}}, \quad \tan \frac{\phi_{fs}}{2} = -\frac{\sqrt{n_s^2 \sin^2 \theta - n_f^2}}{n_f \cos \theta}, \quad \text{TM – polarized.}
\]

Generally, when light propagates along the X axis in
a Z-cut LN thin film, TE and TM guiding modes
represent the ordinary (o) and extraordinary (e) waves,
respectively.

In order to form a guiding mode in the guiding layer,
Eq. (3) has to satisfy the eigenvalue equation\(^2\)

\[
2k_0n_f \cos \theta \cdot h + \phi_{fc} + \phi_{fs} = 2m \pi.
\]

where \(m \ (m = 0, 1, 2\ldots)\) is the mode number. A finite
number of \(m\) means the reflection angle is also limited. The
effective refractive index \(n_{\text{eff}} (n_{\text{eff}} = n_f \sin \theta)\) represents
different modes for a specific waveguide structure. Inci-
dent angles of the FW that can be constrained in the wave-
guide are also discrete. That means that different modes
correspond to different \(\theta\), \(n_{\text{eff}}\) is determined by \(n_f\), \(\theta\), and
\(m\) for a specific waveguide structure (fixed values of \(n_s\), \(n_c\),
and \(h\) from Eq. (6). A searching method called stepwise
extension is used to solve the eigenvalue equation and to
obtain the effective refractive index of the planar wave-
guide. In order to generate an SH wave, we chose an
LN thin film planar waveguide as a specific structure cor-
responding to different wavelengths that could satisfy the
phase-matching condition \(n_{\text{eff,FW}} = n_{\text{eff,SH}}\) (\(n_{\text{eff,FW}}\) and
\(n_{\text{eff,SH}}\) stand for the effective refractive indices of the
FW and SH, respectively).

First, we analyzed the relationship between the wave-
length \(\lambda\) and the effective refractive index \(n_{\text{eff}}\) for specific
thicknesses of the layer \(h\) and polarizations. Figures 2(a)
and 2(b) represent a dispersion relation of zero-order TE
and TM mode which are constrained in a thin film wave-
guide with different thicknesses for FW and SH waves,
respectively. It shows that \(n_{\text{eff}}\) has a linear decrease trend
with increasing \(\lambda\), and \(n_{\text{eff}}\) of the TE-polarized wave is
larger than for the TM-polarized wave for both FW and
SH waves. We also found that the larger thickness, the
larger \(n_{\text{eff}}\).

Then, we analyzed two types of SHG that both meet the
phase-matching conditions. Type I means two incoming
waves of the FW have the same polarizations, which
includes four cases: \(e + e \rightarrow e\), \(e + e \rightarrow o\), \(o + o \rightarrow e\), and
\(o + o \rightarrow o\). Type II means their polarizations are orthog-
ogonal with respect to each other, which includes types
\(e + o \rightarrow o\) and \(e + o \rightarrow e\).

In Fig. 3, we presented three type I mode phase match-
ings for 900 nm thin film. Here, in definition, the case of
\(o + o \rightarrow o\) means that both FW and SH waves are TE-
polarized. The phase matching of \(e + e \rightarrow e\) is invalid
because in LN (point group 3m) there is no corresponding
nonlinear tensor element\(^2\). The lines in different colors
represent the effective indices \(n_{\text{eff}}\) of different modes,
where solid and dashed lines represent FW and SH waves,
Fig. 3. (Color online) Three-mode phase-matching diagrams in 900 nm LN thin film: (a) \( o + o \rightarrow o \); (b) \( o + o \rightarrow e \); (c) \( e + e \rightarrow e \). The solid and dashed lines represent FW and SH waves, respectively, and the black, red, blue, and green lines represent the 0th, 1st, 2nd, and 3rd orders of the space guiding modes. The black points on the intersection stand for nonoverlapping of the space-mode field distribution for the FW and SH waves. The red points stand for the simultaneous satisfaction of the space-mode overlapping and phase-matching modes of the FW and SH waves. (d) The wavelength of the phase-matching point between the 0th FW and 2nd SH waves varies almost linearly with the thickness of the thin film.

respectively. The intersections between different lines are phase-matching points. We found that the overlap integrals of the interaction waves were 0.0681 for the 0th to 2nd modes and only 0.0020 for the 0th to 1st modes. Taking those into consideration, some phase-matching conditions cannot be used to achieve the effective SHG because of the poor overlap of the space-mode field distributions with each other, such as the overlap between odd and even mode fields. We marked the bad overlap with black points. On the contrary, the red points have a good overlap where the SH wave can be generated efficiently. In Fig. 3(c), point A satisfies the phase matching and space-mode fields matching simultaneously, where SHG could exist near 1018 nm in the 900 nm thickness of the LN thin film. Then we show this SHG experiment around 1018 nm in the experimental part, since it utilizes the largest nonlinear coefficient \( d_{33} \).

In Fig. 3(d), we draw the whole natural phase-matching "map," which represents the relationship between the phase-matching wavelength and the thickness of the thin film. As shown in Fig. 3(d), the wavelength of the phase-matching point increases with the increase of thickness in three effective type I phase-matching situations: \( e + e \rightarrow e \), \( o + o \rightarrow o \), and \( o + o \rightarrow e \).

The type II SHG shown in Fig. 4(a) means that the FW of 1.55 \( \mu \)m has the orthogonal polarizations, and includes the two possible phase-matching cases: \( e + o \rightarrow o \) and \( e + o \rightarrow e \). We just checked one case of \( e + o \rightarrow o \). When the FW of 1.55 \( \mu \)m with both the TM- and TE-polarized is incident into LN thin film (as shown in Fig. 1), SH should be TE-polarized. The black solid line stands for the FW with TM- and TE-polarized of zero-order mode fields, while black dashed line stands for TE-polarized SH wave with of the zero-order mode field.

In Fig. 4(a), the two line intersects in point A (839 nm, 1.6373), which means SH generates in the case when the thickness of LN thin film is 839 nm and the effective refractive indices of the FW and SH are both equal to 1.6373. Point A stands for the condition in which SHG could happen. Oppositely, point B cannot generate SHG efficiently due to the lack of space-mode field overlap, as we mentioned above. In particular, the phenomena of the SHG and SPDC could be inverse to each other in nonlinear optics, which is shown in Fig. 4(b). It has been proven that SPDC is one of the most effective methods of generating single-photon pairs, including polarization entanglement photon-pair sources, which plays an important role in quantum communication.

Experimentally, we chose the predicted-mode phase-matching condition of point A in Fig. 3(c) to generate a SH wave by using the largest nonlinear coefficient \( d_{33} \). The experimental setup is shown in Fig. 5(a). At a room temperature of 25°C, a picosecond pulse laser with 2.4 ps at 1018 nm was focused into the single-crystal 5% MgO-doped congruent LN thin film sample of 900 nm thickness (supplied by NANOLN). The first polarizer behind the laser source was used to keep the fundamental light as an extraordinary light. The first lens with a 100 mm focal length (Daheng Optics, GCL-010129) was to focus the pump light captured by camera. The spectra of the pump and the SH waves are shown in Fig. 5(c). The generated SH...
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References