Microwave resonant electro-optic bulk phase modulator for two-dimensional smoothing by spectral dispersion in SG-II

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A special-velocity-matched electro-optic (EO) phase modulator employing a microwave resonant design in lithium niobate is presented. Both the microwave property and phase-modulation performances of the 3.25-GHz modulator agree well with the numerical simulations. Using this modulator in a single-pass configuration with 1-kW microwave drive power, the spectral bandwidth of a 1053-nm, 3-ns pulse-length laser is broadened to 0.13 nm. With a clear aperture of 5 × 5 (mm), the modulator is suited for two-dimensional smoothing by spectral dispersion in high power laser systems.

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By high-frequency phase modulation, the bandwidth of single frequency laser is broadened for two major purposes in high power laser systems, such as SG-II, OMEGA, and NIF. Firstly, a 0.1-nm bandwidth is required to suppress the buildup of stimulated Brillouin scattering (SBS) in large aperture optics. Secondly, additional bandwidth of 0.3~1 nm is required for the application of smoothing by spectral dispersion (SSD) [8]. These modulations could be generated by optical-waveguide phase modulators in master oscillators or bulk phase modulators in pre-amplifiers. Bulk phase modulator is a key component of two-dimensional (2D) SSD [2~4] by applying two separated stages of phase modulations and orthogonal dispersions to meet the beam smoothing requirements in direct drive inertial confinement fusion.

Bulk modulators for 2D SSD need to meet following requirements: 1) an appropriate clear aperture; 2) phase velocity match between the laser and the microwave; 3) a high microwave Q factor [5]. Currently, the clear aperture of the commercial bulk phase modulator [6] is about 1 mm, which is too small to meet the 2D SSD’s requirement. Velocity-mismatch between microwave and laser limits the modulation efficiency. Two different modulator designs were proposed to resolve this problem. By using periodically-poled lithium tantalite, a quasi-velocity-matched phase modulator [7] was achieved. Such a phase modulator with a modulation index of 1.8 rad/kW at 9.4 GHz was used in three-dimensional SSD [8]. Meanwhile, higher Q factor and larger clear aperture were achieved by bulk modulators operating at TE_{10k} microwave resonant mode with velocity-matched design [9,11], where k is the longitudinal mode. A rigid-velocity-matched phase modulator operating at 10.4 GHz was developed for 2D SSD in Omega.

In this letter, an efficient, special-velocity-matched microwave resonant phase modulator operating at TE_{101} resonant mode of 3.25 GHz is presented. The clear aperture is 5 × 5 (mm), which is the biggest reported aperture. In the modulator, microwave phase velocity is approximately 1.5 times of the laser velocity. Compared to a rigid-velocity-matched design, modulation efficiency of this special design is higher by about 12.8%.

When laser with a angular frequency of \( \omega_0 \) is impressed by a sinusoidal phase modulation with a angular frequency of \( \omega_m \), the modulated laser electric field is given by [3]

\[
E_{\text{opt}}(t) = A e^{i(\omega_0 t + \delta \sin \omega_m t)}
\]

\[
= A \sum_{k=-\infty}^{+\infty} J_k(\delta) e^{i(\omega_0 + k \omega_m) t},
\]

where \( J_k(\delta) \) is Bessel function, \( k \) is any integer, and \( \delta \) is modulation index. This expression implies that the laser temporal spectrum is broadened by sinusoidal phase modulation. The spectral bandwidth of phase-modulated laser is proportional to modulation index \( \delta \), approximately given by

\[
\Delta f = \frac{\delta \omega_m}{\pi}.
\]

Due to the transverse electro-optic effect, a high frequency sinusoidal variation of the refractive index is obtained by coupling microwave signal into an EO crystal. When laser beam propagates along the y direction in Fig. 1(a), both the optic and microwave vectors are along the z axis, \( \delta \) is given by

\[
\delta = \beta L \times \left( \frac{\pi n_e^2 r_{33} E_m}{\lambda} \right) / \nu_m.
\]

Where \( L \) is the crystal length, \( n_e \) is the refractive index, \( r_{33} \) is the electro-optic coefficient, \( E_m \) is the electric field, \( \lambda \) is the laser wavelength in air and \( \beta \) is the velocity-mismatch reduction factor [13]. In the microwave resonant electro-optic phase modulator, standing microwaves are formed along the EO crystal, comprised of fields co-propagating and counter-propagating with the laser beam, and \( \beta \) is given by [13]

\[
\beta = \left| \frac{\sin(u_+) + \sin(u_-)}{u_+} \right|, u_\pm = \frac{L \omega_m}{2} \left( \frac{1}{\nu_+} \pm \frac{1}{\nu_-} \right).
\]
where $\nu_{\text{opt}}$, $\nu_{\text{rf}}$ are the laser phase velocity and microwave phase velocity in the EO crystal along the propagation direction, respectively.

Lithium niobate (LiNbO$_3$) was chosen as the EO crystal, whose parameters are listed in Table 1. For a modulation frequency of 3.3 GHz, the relationship between effective crystal length ($\beta L$) and crystal length ($L$) under different velocity-matching conditions ($\nu_{\text{rf}}/\nu_{\text{opt}}$) is shown in Fig. 2. Without velocity matching design (black light-solid curve), the maximum effective interaction length is limited to $\sim$10 mm. Red heavy-solid curve is for a rigid-velocity-matched design, and there is a stage between $L$ = 10 and $L$ = 29 mm. In this area, if the microwave velocity is faster than laser velocity, effective crystal length is lengthened, for violet dash curve ($\nu_{\text{rf}}/\nu_{\text{opt}}$ = 1.3) and green dot curve ($\nu_{\text{rf}}/\nu_{\text{opt}}$ = 1.5). If the laser velocity is faster in this area, effective crystal length is shortened, for blue long-dash dot curve ($\nu_{\text{rf}}/\nu_{\text{opt}}$ = 0.7).

Schematic of a microwave resonant electro-optic bulk phase modulator is shown in Fig. 1 (a). Microwave is coupled into the EO crystal via a waveguide-coaxial adapter and a TE$_{10}$-mode waveguide. For EO crystal (LiNbO$_3$) has a much higher dielectric constant than air, cutoff frequency of the air-filled waveguide section is higher than the operating frequency. Thus, a microwave resonant cavity is formed at the EO crystal, working at a TE$_{10}$ mode. Compare to other bulk modulator designs, microwave resonant EO phase modulator has following advantages: 1) phase velocity matching between the laser and microwave is achieved by controlling the EO crystal dimension, modulator could operate at TE$_{10k}$ resonant mode; 2) due to the high microwave $Q$ factor, this modulator has much higher modulation efficiency.

The design of a microwave resonant EO phase modulator could be decomposed into the resonant cavity and the microwave coupling design$^{[9]}$. Cavity design is achieved by setting the appropriate dimension of the crystal, shown in Figs. 1(b) and (c). Ignoring phase shifts associated with the reflections at the cutoff-waveguide, the length of the crystal is an integer multiple of half-wavelengths of the microwave. For a 3.3-GHz TE$_{101}$ mode LiNbO$_3$ modulator with the velocity-matched design, crystal length is about 21 mm which is in the stage area shown in Fig. 2. In this area, microwave velocity could be faster than the laser. According to Fig. 2, $\nu_{\text{rf}}/\nu_{\text{opt}}$ = 1.3 is selected. The microwave phase velocity in the crystal is adjusted by setting the width of the crystal ($w$), given by$^{[10]$

$$\nu_{\text{rf}} = \frac{c}{\sqrt{\varepsilon_{33}} \sqrt{1 - (f_{\text{cutoff}}/f_{\text{mod}})^2}},$$

$$f_{\text{cutoff}} = \frac{c}{2w \sqrt{\varepsilon_{33}}}$$

where $f_{\text{mod}}$ is the operating frequency of the modulator, $f_{\text{cutoff}}$ is the cutoff frequency of the crystal, and $c$ is the light velocity in air. To match the laser velocity in the crystal, $c/n_a$, the crystal width is about 9.4 mm. To ensure the TE$_{10}$ mode, the crystal height needs to meet the condition of $c/2h \sqrt{\varepsilon_{33}} < 3.3$ GHz. Considering the clear aperture requirement of SSD, $h$ is set 5 mm. Except for the two clear aperture, all the other four sides of the crystal are gold coated. The transverse section of the cutoff waveguide is a bit larger than the LiNbO$_3$ crystal.

In Fig. 1 (a), the input waveguide consisted of a waveguide coaxial adapter, an E-plane tapered waveguide and an E-plane waveguide bend. By the tapered waveguide, the height of the waveguide is shortened from the standard 34 to 10 mm. An isotropic numerical simulation is performed by using electromagnetic

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**Table 1. Parameters of Lithium Niobate**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO Coefficient (pm/V)$^{[14]}$</td>
<td>$r_{33} = 28.8$–$30.8$</td>
</tr>
<tr>
<td>Refraction Index$^{[14]}$</td>
<td>$n_e = 2.1561$</td>
</tr>
<tr>
<td>Relative Dielectric Constant$^{[15]}$</td>
<td>$\sqrt{\varepsilon_{11}} = 6.64 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>$\sqrt{\varepsilon_{33}} = 5.11 \pm 0.06$</td>
</tr>
<tr>
<td>Loss Tangent$^{[15]}$</td>
<td>0.004</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Schematic of a microwave resonant electro-optic bulk phase modulator.

**Fig. 2.** Relationship between effective crystal length and original crystal length for different velocity-matching conditions.

**Fig. 3.** Simulated microwave reflectivity versus frequency.
simulation software. To increase the coupling efficiency, the crystal is extended into the input waveguide for 2 mm. According to the simulation result, TE_{101} resonant frequency of 3.32 GHz is achieved when the crystal length is 18 mm with a Q factor of 114.5. The simulated microwave reflectivity versus frequency bandwidth from 3.1 to 3.5 GHz is plotted in Fig. 3. The results indicate that the modulator has a high microwave coupling efficiency at the TE_{101}.

The microwave properties of the modulator were measured by a microwave vector network analyzer. TE_{101} mode of 3.25 GHz and corresponding S_{11} of −18 dB was achieved for an extending distance of ≈1.8 mm with a Q factor of 118. The resonant frequency of 3.25 GHz is lower than simulated results by 2.1%, and the measured Q factor is higher than simulated results by 3%. Compared to the design of 3.3 GHz, the actual phase velocity of the microwave is higher than the design value from Eq. (5) by 16.7%. Thus, the real velocity-matching condition is ν_m/ν_{opt} = 1.5, whose effective length was predicted by the green dot curve in Fig. 2 with a β of 1.32. The cause of the inconsistent between the tested frequency and simulated value are as follows: First, the actual dielectric constant of the LiNbO_{3} could differ from the simulations. Second, to integrate the LiNbO_{3}, the actual cutoff waveguide is a bit larger than the simulations.

A Fabry-Perot (FP) etalon with a free spectral range (FSR) of 60 GHz at 1053 nm was used to measure the phase-modulation performance. Using the modulator in a single-pass modulation configuration with 1-kW microwave drive power, the spectral bandwidth of a 1053-nm, 3-ns pulse-length laser is broadened to 0.13 nm. With a clear aperture of 5 × 5 (mm), the modulator is suited for 2D SSD in high power laser systems.

In conclusion, an efficient, special-velocity-matched microwave resonant bulk phase modulator operated at TE_{101} resonant mode of 3.25 GHz is successfully developed. Both the microwave properties and phase-modulation performances agree well with the numerical prediction. By the optimized velocity-matching design, a velocity-mismatch reduction factor β of 1.32 is expected, which is higher than a rigid-velocity-matched design by 12.8%. Using this modulator in a single-pass configuration with 1-kW microwave drive power, the spectral bandwidth of a 1053-nm, 3-ns pulse-length laser is broadened to 0.13 nm. With a clear aperture of 5 × 5 (mm), the modulator is suited for 2D SSD in high power laser systems.

References
5. D. Kajfez, Q Factor (Vector Fields, Oxford, MS, 1994).