Electro-optic measurement of averaged duty ratio for periodically poled crystals

Chia-Tsung Liu[1], Chia-Lun Tsai[1], Jui-Yu Lai[1,2], Yen-Hung Chen[3], and Shang-Da Yang[1]
[1]*Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan*
[2]*HC Photonics Corp., R&D Division, 4F, No.2, Technology Rd. V, Hsinchu Science Park, Hsinchu 30078*
[3]*Department of Optics and Photonics, National Central University, Jhongli 320, Taiwan.*
lct820827@gmail.com

Abstract: A non-invasive electro-optic method is proposed to measure the averaged duty ratio for periodically poled crystals. The measured (expected) averaged duty ratios of two samples are 67.95%/32.05% (75/25) and 55.02%/44.98% (50/50).
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1. Introduction

Quasi-phase matching (QPM) is a widely used technique for wavelength conversion that allows for the employment of the highest nonlinear tensor component (e.g. d_{33} in $LiNbO_3$) and prevents the undesirable energy walk-off from happening. To perform QPM, periodic poling [1] is the most common technique, where a high voltage is applied to the periodical electrode pattern on the surface of ferroelectric material to produce inverted micro structure inside the crystal. The nonlinear conversion efficiency of a QPM device strongly relies on the quality of the periodical structure. For example, the effective nonlinear coefficient d_{eff} of a first-order QPM grating made of periodic poled $LiNbO_3$ (PPLN) is $(2/\pi)\times d_{33}$. In reality, the systematic and random fabrication imperfection [2] could strongly degrade d_{eff}. As a result, diagnostic techniques for poling quality are of practical importance in terms of the quantitative evaluation of the device performance. It particularly matters for (1) nonlinear processes involving with short wavelengths (where the domains are too small to be precisely controlled) and (2) higher-order QPM (where the performance is much more sensitive to the averaged duty error). Several non-invasive methods have been proposed to measure the poling structure. For example, nonlinear spectral interferometry [3] can reveal the spatial distribution of the domain structure by measuring the phase-matching spectral phase. Statistical analysis of phase-matching power spectral pedestal [4] gives the random poling error. However, both methods rely on demanding laser source (femtosecond laser plus high nonlinear fiber, wavelength tunable CW laser) to generate the nonlinear signal, and neither of them could provide the averaged duty ratio that dominates the conversion efficiency. In this work, we propose a simple electro-optic (EO) method to quantitatively estimate the average duty ratio by measuring the relative phase difference change of the e-wave and o-wave. This technique only needs a low-power CW laser at any wavelength transparent for the material and is applicable to any periodic QPM structure. Our proof-of-concept experiment shows that a second-order and a first-order PPLN (HC Photonics) has an averaged duty ratio of 67.95%/32.05% and 55.02%/44.98% (versus the expected 75/25 and 50/50).

2. Theory

When an external field V/d is applied along the optic axis of the crystal, the refractive index changes for e-wave and o-wave are formulated as

$$\Delta n_e = -\frac{1}{2}\gamma_{33} n_e^3 \frac{V}{d}, \qquad \Delta n_o = -\frac{1}{2}\gamma_{13} n_o^3 \frac{V}{d}$$

For a periodically poled structure, the fields in the poled and unpoled regions have the opposite signs. As a result, the refractive index changes can cancel with each other if the poling duty ratio is perfectly 50/50. For an imperfect structure, the phase difference between the e-wave and o- wave is

$$\Delta\varphi(V) = -\frac{1}{2} k L_{eff} \frac{V}{d} (\gamma_{33} n_e^3 - \gamma_{13} n_o^3), \; L_{eff} = \frac{L_+ - L_-}{L_+ + L_-} L$$

where L_{eff} is the effective crystal length, L_+ and L_- are the total lengths of the positive and negative domains, respectively. If the input polarization is 45 degree to the optic axis and a linear polarizer has been placed 45 or -45 degree to the optic axis after the crystal, the transmitted optical power varies with the applied voltage via:

$$P(V) = P_0 + P_0 \cos\varphi(V)$$

3. Experimental setup and results

Figure 1(a) is the experimental setup. A 532 nm continuous-wave (CW) laser is chosen as the light source. A thin BK7 glass is placed at Brewster angle (56.6^o) such that the reflected beam is linearly polarized. A half wave plate controls the input polarization as 45 degree to the optic axis. Three 5 mol% MgO doped PPLN samples have been measured in this experiment. (1) 5.17 mm long, 0.3 mm thick, poling period Λ is 3.22 μm with an expected 75/25 duty. (2) 5 mm long, 0.5 mm thick, poling period is 5.26 μm with an expected 50/50 duty. (3) 10 mm long, 2 mm thick bulk without poling (for reference). A temperature controller is used to control the sample at a stable temperature 25℃ to reduce the temperature interference. A PBS is placed 45^o against the optic axis and a calibrated photodetector is used to measure the output power.

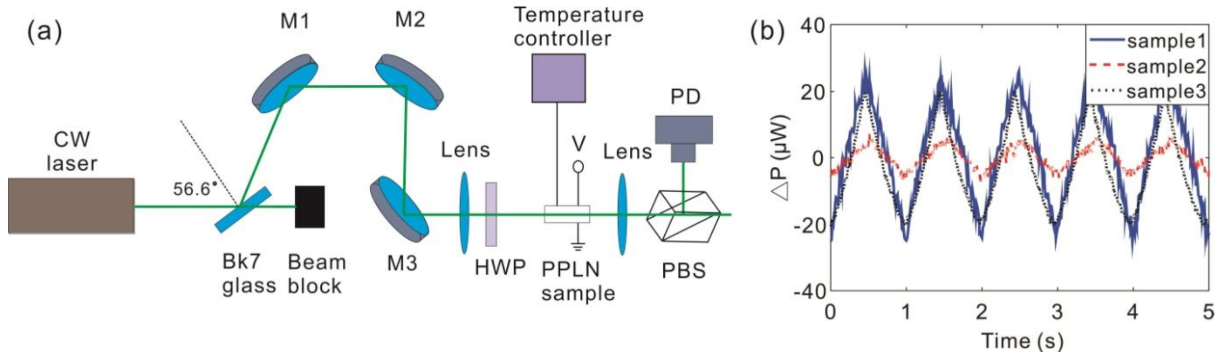

Fig. 1. (a) Experimental setup. M#, mirrors; HWP, half wave plate; PBS, polarization beam splitter; PD, photodetector. (b) The output power variation in the presence of 100 V, 1 Hz triangular voltage signal.

Figure 1(b) illustrates the output power variations of the three samples after applying a triangular voltage signal with 100 V amplitude and 1 Hz frequency. By knowing power variations we can get the phase difference. Since to the EO coefficient cannot be absolutely accurate, the result of Sample 3 (black-dotted) is used as a reference such that the duty ratios of other samples can be obtained by comparison. By taking the crystal length and the thickness into account, the power variations of ideal Samples 1 and 2 (blue-solid line, red-dashed line) and the phase difference should be 1.66 and 0 times of that of Sample 3. The experiment gives 1.196 and 0.207 instead, corresponding to the real duty ratios of 67.95%/32.05% and 55.02%/44.98%, respectively.

3. Conclusion

We propose and demonstrate a simple EO method to measure the averaged duty ratio for QPM gratings. Taking an un-poled bulk crystal as the reference, the measured duty ratios of two PPLNs with expected duty ratios of 75/25 and 50/50 are actually 67.95%/32.05% and 55.02%/44.98%, and the duty ratios measured under microscope are 65.7%/34.3% and 51.6%/48.4%, respectively.

4. References

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