Distributed-feedback optical parametric oscillation by use of a photorefractive grating in periodically poled lithium niobate

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We report a demonstration of distributed-feedback (DFB) optical parametric oscillation (OPO) by writing photorefractive gratings in periodically poled lithium niobate (PPLN). The photorefractive DFB structures were fabricated by illumination of PPLN with UV light through a photomask and by writing of PPLN with UV-light gated interfering laser beams at 532 nm. Evidence of OPO was observed from the spectral narrowing at the 1438.8- and the 619.3-nm signal wavelengths from 1064- and 532-nm-pumped PPLN crystals with the DFB grating periods phase matched to the 4084.5- and 3774-nm idler wavelengths, respectively.

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Distributed-feedback[1] (DFB) lasers have the advantages of simplicity and single-longitudinal-mode operation. In a DFB laser, the mirrors are eliminated by implementation of a DFB grating throughout the entire laser medium. Because of the distributed optical feedback in both longitudinal directions from the grating, a DFB laser may oscillate near the Bragg wavelength, $\lambda_s = 2n\Lambda_{\mathrm{DFB}}$, where Λ_{DFB} is the DFB grating period and n is the refractive index of the laser medium. The DFB structure has been widely used in diode lasers, which are capable of generating single-frequency, kilohertz-linewidth laser radiation for a variety of applications. However, the wavelength of a diode laser is limited by the bandgap of the semiconductor material and cannot be varied with an arbitrary choice of the DFB grating period. Yet if one could implement a DFB grating in the nonlinear optical medium of an optical parametric oscillator, one would achieve single-frequency emission at any wavelength in the tuning range of the oscillator.

Since 1995, the quasi-phase-matched[2] nonlinear frequency-conversion technique has advanced rapidly and been well developed. Solid-state laser-pumped optical parametric generation (OPG) and oscillation from periodically poled lithium niobate (PPLN) have provided efficient and widely tunable laser sources.[3,4] In the mid-infrared wavelengths, the spectral width of PPLN OPG may exceed several nanometers.[5] Quasi-phase-matched optical parametric oscillation (OPO) is a popular means of obtaining efficient narrow-line laser radiations.[6] To achieve single-longitudinal-mode OPO, one usually has to adopt a more complicated resonator design.[7,8] Since lithium niobate is a photorefractive material,[9] it is possible to write a photorefractive DFB structure in a PPLN crystal. In this Letter we show two PPLN DFB optical parametric oscillators with photorefractive DFB gratings in PPLN crystals. One photorefractive DFB grating was fabricated by illuminating UV light through a photomask atop the PPLN, and the other was written into the PPLN crystal by means of interfering laser beams at 532-nm wavelength. Although laser oscillation in erbium-doped lithium niobate with photorefractive Bragg reflectors has been demonstrated,[10] to the authors' best knowledge, this Letter reports the first successful operation of DFB OPO in PPLN. In the following discussion, we define the shorter-wavelength output generated from the OPO as the signal and the longer-wavelength output generated as the idler.

In the UV photomask scheme, incoherent UV radiation from a 20-W mercury lamp illuminated a photomask with a 1-μm-period, 50% duty-cycle chromium grating. The mercury lamp was covered with a UV filter that is transparent to the 365-nm mercury line. With the UV filter, the incident intensity on the photomask was $\sim 0.3\ \mathrm{W/cm^2}$. The photomask was in contact with a 4-cm-long, 0.5-mm-thick, 28-μm-period, uncoated and end-polished PPLN crystal with the chromium grating vector aligned with the quasi-phase-matched grating vector in the crystallographic x direction. While the UV radiation illuminated the photomask, we raised the PPLN crystal temperature from 20 to 160 °C within 3 min and decreased the temperature from 160 to 20 °C over a 2-h duration. The UV-induced photorefractive DFB grating was thus fixed in the PPLN. The 1-μm DFB grating period allowed oscillation of the 4.085-μm idler wavelength in the 1064-nm-pumped PPLN OPO at 115.4 °C. The corresponding signal wavelength was 1438.8 nm. Pumping the DFB PPLN with a 9-μJ/pulse, 730-ps pulse width passively Q-switched Nd:YAG laser, we observed that the DFB OPO signal was generated at 1438.8 nm. The signal spectra were measured by use of an InGaAs detector after a CVIDK480 1/2-m grating monochromator. The resolution of the monochromator was 0.3 nm, with a 10-μm slit opening and a 300-lines/mm infrared grating. The 730-ps pump pulse length is comparable to the round-trip time in the 4-cm-long PPLN crystal and does not establish parametric oscillation from the uncoated PPLN end faces.

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Figure 1 shows the OPO and the OPG signal spectra at different temperatures. It is evident from Fig. 1 that, although the OPG wavelength was shifted by temperature, the OPO signal wavelength remained unchanged because of the photorefractive DFB grating in the PPLN. At 115.4 °C, the OPG wavelength overlapped the OPO signal wavelength, and the conversion was significantly enhanced by a factor of 3. The measured spectral width of the DFB OPO signal was 0.3 nm, and that of the OPG signal was 3 nm. Figure 2 shows the pulse energy of the DFB OPO signal at 1438.8-nm wavelength versus the pump energy at the 1064-nm wavelength. The energies shown in the plot are internal to the PPLN crystal. At a pump energy of 6.75 μJ, the output signal energy was 1 μJ, corresponding to 15% signal conversion efficiency. We measured the 1438.8-nm OPO signal after a 5-mm-thick dichroic glass mirror installed at 45° with respect to the pump beam. The dichroic mirror removes 99.5% of the 1064-nm pump power, transmits 95% of the 1438.8-nm signal power, and absorbs the 4-μm idler power. We believe that the 6-kW pump threshold is due to the 0.15-cm^{-1} absorption coefficient at the 4.085-μm idler wavelength and nonideal photorefractive DFB grating in the PPLN crystal. In our observation, the photorefractive DFB grating was erasable. When the PPLN was heated (to 180 °C) for 3 h, the DFB OPO signal at 1438.8 nm became much weaker than that in Fig. 1 but still existed at the same wavelength, with a signal-to-noise ratio of 2 when the temperature was 95 °C. Near 115 °C, we continuously operated the DFB OPO for ~1.5 h without observing any degradation of the DFB OPO output.

With the DFB grating vector in the crystallographic x direction, one would expect that the DFB grating results from the space-charge field in the x direction, E_x. However, the E_x-induced refractive-index change for a z-polarized pump field is a second-order effect in lithium niobate, given by

$$\Delta n_z = n_o{}^2 n_e{}^3 (r_{51} E_x)^2/2\,, \tag{1}$$

where n_0 and $n_e \approx 2.2$ are the ordinary and extraordinary refractive indices, respectively, and $r_{51} \approx 32$ pm/V is the electro-optic coefficient of lithium niobate. In the steady-state, thermal-diffusion-dominated, and nondepleted-carrier approximation, the space-charge field is approximately of the order of $E_x \approx 2\pi k_B T/(\Lambda q) \approx 10^5$V/m, where k_B is the Boltzmann constant, q is the electron charge, $T \approx 400$ K is the crystal temperature, and $\Lambda = 1$ μm is the DFB grating period.[11] Although this space-charge field rotates the index ellipsoid of lithium niobate and slightly depolarizes the incident optical field, the index change seen by the laser is merely $\Delta n_z \approx 10^{-9}$, according to Eq. (1). However, our numerical simulation shows that the depth of the DFB grating is less than 20 μm from the surface of the PPLN crystal because of diffraction of the mercury 365-nm light by the 1-μm mask. This result suggests that a surface photorefractive grating instead of a bulk photorefractive grating was formed in the PPLN crystal. In the experiment we indeed observed a fading DFB OPO signal when we moved the pump beam away from the surface. Despite the shallow DFB grating, we still observed a TEM_{00} mode at the DFB OPO output when pumping through the 0.5-mm-thick PPLN with an estimated waist radius of 150 μm. With the photorefractive charges accumulated on the PPLN surface, a z-component space-charge field E_z may induce a first-order refractive-index change in PPLN, given by

$$\Delta n_z = n_e{}^3 r_{33} E_z/2 \approx 10^{-5}, \tag{2}$$

where we use $r_{33} \approx 31$ pm/V and $E_z \approx E_x \approx 10^5$ V/m for calculation. This amount of refractive-index change is much larger than that calculated from Eq. (1) for the bulk photorefractive effect. Indeed, it has been reported in the past that surface photorefractive-index change can be several orders of magnitude larger than the bulk photorefractive-index change.[12] The distributed optical feedback in our PPLN optical parametric oscillator was similar to that

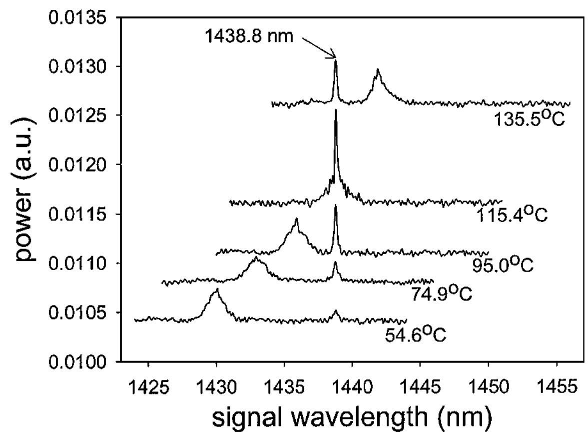

Fig. 1. Signal spectra of the 1064-nm-pumped OPG and DFB OPO at different temperatures. The measured spectral width of the OPG was 3 nm and that of the DFB OPO was 0.3 nm. The DFB OPO signal wavelength, defined by the DFB grating, remained unchanged when the temperature was varied.

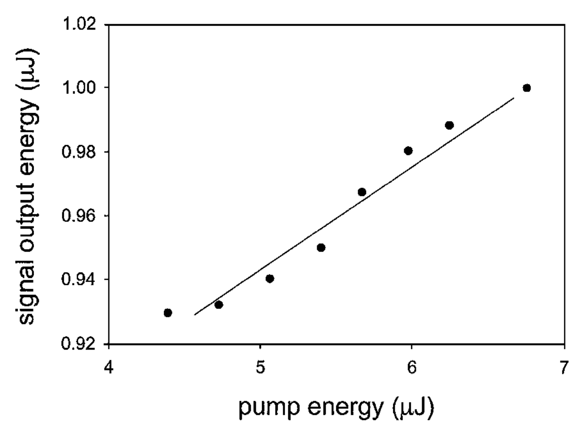

Fig. 2. 1438.8-nm DFB OPO signal energy versus pump energy phase matched at 115.4 °C. With the internal pump energy of 6.75 μJ, the DFB OPO signal energy was 1 μJ. The pump threshold energy was 4.5 μJ, corresponding to 6-kW pump power.

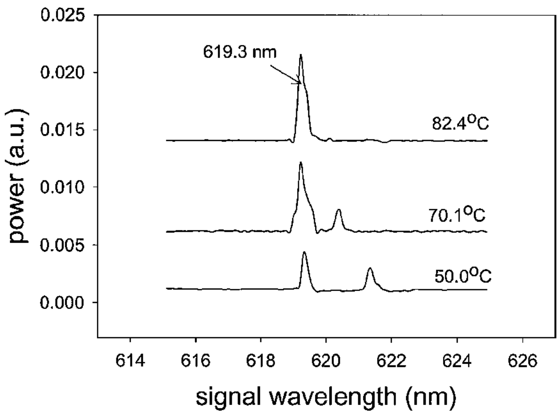

Fig. 3. Signal spectra for the 532-nm-pumped PPLN DFB OPO at different temperatures. Again, the DFB OPO signal wavelength is fixed at 619.3 nm regardless of the change of the temperature. However, the OPG signal, the smaller one to the right of the 619.7-nm OPO signal, changes its position as the temperature varies.

in a DFB diode laser with a corrugated grating atop the gain medium.

To investigate the possibility of obtaining a DFB optical parametric oscillator by using the bulk photorefractive effect in PPLN, we tried to write the photorefractive DFB grating by using interfering laser beams at the 532-nm wavelength. We used a cylindrical lens to shape the spherical laser beam into an elliptical beam with an approximately 1:50 axis ratio. Then we split and recombined the 200-mW, 532-nm laser with a 34° angle to produce 0.913-μm-period interference fringes on a 5-cm-long, 0.5-mm-thick, 11-μm-period, uncoated and end-polished PPLN crystal. The peak intensity of the interfering laser beam was ~0.5 W/cm^2. The 0.913-μm-period DFB grating was designed to oscillate the 3.778-μm OPO idler wavelength in the 532-nm-pumped PPLN at 82 °C. The pump laser was a passively Q-switched, frequency-doubled Nd:YAG laser, producing 2-μJ pulse energy in the PPLN crystal with a 6.59-kHz repetition rate and 430-ps pulse width. The interfering 532-nm laser beams produced a periodic space-charge field in the x direction in the bulk of the PPLN crystal. Although the temperature-dependent OPG signal near 620 nm was clearly seen in our experiment, we did not observe any evidence of DFB OPO because of the trivial photorefractive-index change given by Eq. (1).

While keeping the 532-nm interference fringes in the PPLN crystal, we illuminated the PPLN $+z$ surface with UV light of intensity 53 mW/cm^2 and again observed the DFB OPO signal at the output. The UV light at the 365-nm wavelength was strongly absorbed at the lithium niobate surface and induced a surface DFB grating through the so-called two-photon photorefractive writing scheme.[13] Figure 3 shows the OPO and OPG signal spectra from the PPLN at different temperatures. It is evident from Fig. 3 that, although the OPG wavelength was tuned by temperature, the DFB OPO signal wavelength at 619.3 nm again remained unchanged because of the photorefractive DFB grating. At 82.4 °C, the OPG wavelength overlapped the OPO signal wavelength. When we translated the pump beam transversely in the $-z$ direction, the DFB OPO signal was reduced rapidly because of the shallow photorefractive DFB grating formed at the $+z$ surface. In this experiment the DFB OPO signal's spectral width is also 0.3 nm.

In summary, we have demonstrated two DFB PPLN optical parametric oscillators by writing photorefractive gratings in PPLN crystals. The photorefractive DFB structures were fabricated near the surface of a PPLN crystal by UV illumination through a photomask and by the two-photon photorefractive writing scheme. Evidence of DFB OPO was observed at the 1438.8- and 619.3-nm signal wavelengths from the 1064- and the 532-nm-pumped PPLN, respectively. With a passively Q-switched or mode-locked pump laser, OPO might not occur because of the short laser-pulse length and thus the limited gain length. In both experiments, OPO was demonstrated in 4- and 5-cm PPLN crystals with a pump pulse width of a few hundred picoseconds. In addition, the high index change in the surface photorefractive DFB grating could be suitable for realizing single-frequency low-threshold continuous-wave waveguide DFB OPO in PPLN.

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