Bidirectional, synchronously pumped, ring optical parametric oscillator

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We report the operation of a bidirectional femtosecond pulsed ring optical parametric oscillator based on periodically poled lithium niobate, pumped alternately with nonsimultaneous pulses from a Ti:sapphire mode-locked laser. A beat note between the two counterpropagating beams attests to a gyro response without dead band. The sensitivity of the device to differential phase changes is demonstrated by measurement of the nonlinear index of lithium niobate. © 2001 Optical Society of America

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A ring laser operating in a bidirectional mode can be thought as a differential spectrometer, provided that there is no phase or frequency coupling between oppositely traveling waves. The resonance condition imposes that the wavelength λ_+ and λ_- in either direction be an integer divider of the corresponding optical perimeter P_+ and P_-. If the two outputs of this ring laser are made to interfere on a detector, a beat note of frequency $\Delta\nu$ will be measured, equal to the difference between the two optical frequencies $\nu_\pm = c/\lambda_\pm$:

$$\Delta\nu = \nu\frac{\Delta P}{P}, \tag{1}$$

where ν is the average optical frequency.

Bidirectional operation without phase coupling is never observed in solid-state cw lasers, because (i) backscattering from all optical components causes phase coupling from one wave into the oppositely traveling one and (ii) stable bidirectional operation is prevented by the homogeneously broadened gain line. In the case of mode-locked lasers, however, bidirectional operation has been demonstrated even for Kerr-lens mode-locked solid-state lasers,[1,2] because gain competition can be prevented by having each pulse traverse the amplifying medium at equal time intervals. The phase coupling between counterpropagating beams is avoided by having the pulses meet in a moving mode-locking element,[3] thus averaging the phase of the backscattering (a kind of random phase dithering).

The two outputs can also be made to interfere on a detector to record a beat note as given by Eq. (1). Experiments with ring[2] and linear[4] Ti:sapphire femtosecond lasers have demonstrated the exceptional sensitivity of these lasers as differential interferometers. A resolution of $\Delta\nu = 1.5$ Hz for the beat note implies that a differential phase shift of $\Delta\nu \times \tau_{\mathrm{RT}} \geq 1.5 \times 10^{-8}$ can be measured (where τ_{RT} is the cavity round-trip time). In metrological applications, this resolution in optical path, according to Eq. (1), is better than 0.1 pm (10^{-4} nm).

The fact that the observed spectral width of the beat note is as small as a few hertz is another manifestation of the near-perfect regularity of the frequency comb of a femtosecond laser.[5] Indeed, the beat frequency is an average of the difference frequencies of the corresponding teeth of the two output combs of the laser, and the bandwidth of that signal is an upper limit to the irregularities of the frequency combs.

A Ti:sapphire laser with an intracavity saturable absorber jet is not a practical device for applications. A synchronously pumped optical parametric oscillator (OPO) (Fig. 1) is an attractive alternative. It offers the possibility to decouple the relative phase and repetition rates of the oscillating signals, without the need for any moving element. The position of the crossing point of two counterpropagating trains is simply determined by optical delay lines, rather than by a saturable absorber[3] or a nonlinear crystal.[2] The mode frequencies are still set by the cavity. Another advantage is the tunability, which is important for detecting ultralow magnetic fields, where the laser radiation has to be tuned to a narrow atomic transition.

A mode-locked Ti:sapphire laser, operating at 790 nm, is used to pump the ring OPO bidirectionally, with pulses of 175-fs duration at a repetition rate of 110 MHz. The pump laser can provide 1 W of average power in a linear configuration. The isolation between OPO and pump, provided by a single-stage Faraday rotator, was marginal in the case of a linear pump laser. Therefore, a preferred configuration was with the pump in a unidirectional ring configuration, less sensitive to feedback, which provided an average

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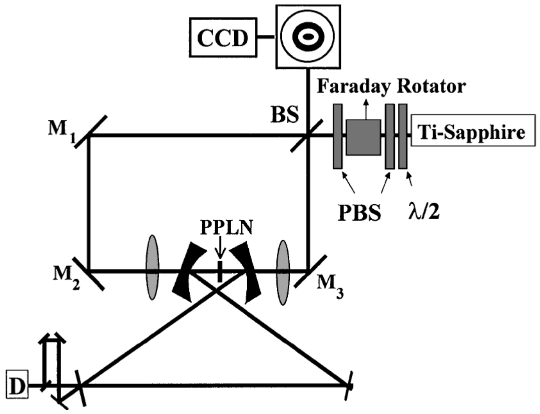

Fig. 1. Illustration of the OPO cavity pumped by the Ti:sapphire laser. The reflected and transmitted parts of the beam splitter, BS, are focused into the periodically poled $LiNbO_3$ (PPLN) crystal via mirrors M_1-M_2 and mirror M_3, respectively. The difference between the two optical paths determines the crossing point of the signal pulses in the OPO cavity. The two output pulses are made to interfere on a detector, D, after an optical delay line brings them in coincidence. In exact alignment, BS and mirrors M_1, M_2, and M_3 constitute an antiresonant ring, the output of which can be monitored with a CCD. Since the antiresonant ring has 100% reflection, an optical isolator, consisting of a Faraday rotator between two polarizers, is needed to protect the oscillator from the feedback.

power of only 400 mW. The pump beam is split into two parts that are sent in opposite directions into a 0.8-mm-long OPO crystal, periodically poled $LiNbO_3$, with a period of 19.75 μm. Stabilizing the crystal temperature at 373 K prevents photorefractive damage and results in a quasi-phase matching condition for generation of a signal near 1.4 μm.

Two outputs corresponding to opposite circulation in the OPO cavity are appropriately delayed with respect to each other before being recombined on a InGaAs photodiode that collects the interfering signals. Compared with a laser, the OPO ring presents peculiar characteristics, which will be detailed below: (i) sensitivity to the pump focal spot, (ii) feedback to the pump laser, and (iii) cavity length tuning.

In a conventional laser, the two oppositely propagating waves experience the same gain medium. Therefore, the two counterrotating beams are operating on the same transverse mode. In the case of the OPO, the gain volume is the focal spot of two independent beams, which have to coincide. A minor displacement of one of the pump spots results in a large change in beat signal. This spurious beat note is minimized if the two counterpropagating pumps are exactly collinear, which implies that the cavity consisting of beam splitter BS and the three turning mirrors, M_1, M_2, and M_3, is an antiresonant ring.[6,7] The alignment of the pump is optimized by monitoring the output of the antiresonant ring. Since the antiresonant ring reflects into the laser one should isolate the pump laser to maintain mode-locked operation. The 10^{-4} isolation provided by a single-stage isolator is not sufficient to ensure stable continuous operation when the pump laser is in a linear configuration. Continuous mode-locked operation can be maintained with the Ti:sapphire laser modified into a ring configuration with four intracavity prisms operating in unidirectional mode.

One might wonder whether a Sagnac effect in the antiresonant ring might alter the gyro response of the OPO. It should be remembered that the phase of the pump and that of the OPO signal generated or amplified in the periodically poled $LiNbO_3$ crystal are uncorrelated. In a frame of reference where the signal wave repeats itself in phase at each round trip, its electric field at the round trip of index m is $E_{s,m} = \mathcal{E}_{s,m}\exp(i\omega_s t)$. To a linear approximation, the signal field at the next round trip, after amplification in the OPO crystal of index n_0, nonlinear susceptibility $\chi^{(2)}$, and length l is

$$E_{s,m+1} = E_{s,m} + l\frac{\omega}{2n_0c}\chi^{(2)}E_{p,m}E^*_{i,m}. \qquad (2)$$

If δ_m is a random phase fluctuation of the pump at the round trip m, the generated idler at that particular cycle will be

$$\begin{aligned} E_{i,m} &= \mathcal{E}_{p,m}\exp(i\omega_p t + \delta_m)\mathcal{E}^*_{s,m}\exp(-i\omega_s t) \\ &= \mathcal{E}_{p,m}\mathcal{E}^*_{s,m}\exp(i\omega_i t + \delta_m). \end{aligned} \qquad (3)$$

Inserting Eq. (3) into the generation term of Eq. (2), we find that, indeed, the phase factor of the gain factor is independent of δ_m.

The wavelength of the circulating signals in the OPO is partly set by the phase-matching condition, partly by the cavity mismatch, while the mode frequency is set by the OPO cavity. The laser can be temperature tuned or pump tuned. Using the Sellmeier fit,[8] we calculate the temperature and pump wavelength tuning curves for a fixed grating period of 19.75 μm. The threshold dependence of the pump wavelength, measured at a temperature of 420 K, shows an average pump power of 350 mW at 775 nm, decreasing nearly linearly to a minimum of 150 mW at 785 nm. The maximum pump depletion is approximately 35%. The signal wavelength is centered at 1.4 μm with a pulse duration of 220 fs (without group-velocity dispersion compensation). Using a 1% output coupler, we find that the average power of the signal is approximately 20 mW when the average pump power is 200 mW in each direction.

As previously reported,[9] the signal and idler wavelengths show a very strong dependence on cavity detuning. This dependence is attributed to the group-velocity dispersion of the crystal: as the cavity length is changed, another signal wavelength will have the same round-trip frequency as the pump pulses. A change of 26 μm in cavity length is sufficient to shift the signal frequency by an amount equal to its bandwidth. This sensitivity results in amplitude fluctuations of the signal of the order of 30%, which also affect the beat note. The bandwidth of the beat note (Fig. 2) is approximately 10 kHz. Such a large bandwidth can only be attributed to the third-order

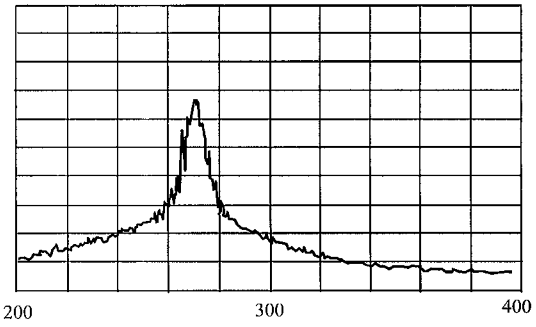

Fig. 2. Spectrum of the beat note as observed by a spectrum analyzer. The vertical scale is 10 dB/div.

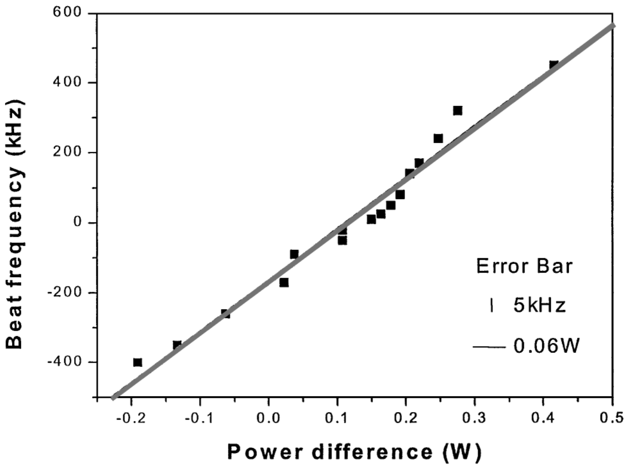

Fig. 3. Plot of the beat note versus the difference in power between counterpropagating beams.

nonlinearity of the $LiNbO_3$ crystal, which is the only intracavity element. Indeed, the amplitude fluctuations of the signal cause differential phase shifts between counterpropagating beams. If I_+ is the peak intensity of the clockwise-circulating pulse in the OPO cavity, and I_- is that of the counterclockwise-circulating pulse, the nonlinear index n_2 of lithium niobate causes a beat-note frequency $\Delta\nu_{\mathrm{NL}}$ equal to

$$\Delta\nu_{\mathrm{NL}} = \frac{2\pi d}{\lambda} n_2 (I_+ - I_-) \frac{1}{\tau_{\mathrm{RT}}}, \tag{4}$$

where d is the length of the lithium niobate crystal. Stable operation of the OPO as a ring laser gyro will thus require active stabilization of the OPO cavity to that of the pump.

The synchronously pumped ring laser itself provides an accurate means of determining the nonlinear index of the OPO crystal used. Figure 3 shows a plot of the beat note versus the difference in power between counterpropagating signals. The general slope of the data corresponds to a nonlinear index of 8.5×10^{-15} cm^2/W. The main sources of error are related to the amplitude instability of the OPO, itself due to cavity length fluctuations. Active stabilization of the cavity will greatly improve the accuracy of the measurement.

Despite the large noise observed in this preliminary demonstration of a bidirectional OPO femtosecond ring laser, this instrument holds promises as a metrological tool. As shown by Wachman *et al.*,[10] active stabilization of a synchronously pumped OPO can reduce its amplitude noise by several orders of magnitude. With further stabilization of the frequency of the signal,[5] the OPO signal in one direction can be tuned to resonance with an atomic vapor. In addition to metrology applications such as measurements of minute rotation rates and picometer displacements,[3] very sensitive magnetic field sensing is possible. The technique is to insert the atomic vapor between quarter-wave plates in the cavity so that each intracavity circulating wave has opposite circular polarization in the vapor. A level structure with a Zeeman split ground or upper state should be chosen. In the presence of a magnetic field, the oppositely circularly polarized countercirculating pulses will experience a difference phase shift, resulting in a beat note that is proportional to the magnetic field.

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References

1. M. J. Bohn and J.-C. Diels, Opt. Commun. **141,** 53 (1997).
2. M. J. Bohn, R. J. Jason, and J.-C. Diels, Opt. Commun. **170,** 85 (1999).
3. S. Diddams, B. Atherton, and J.-C. Diels, Appl. Phys. B **63,** 473 (1996).
4. M. J. Bohn, J.-C. Diels, and R. K. Jain, Opt. Lett. **22,** 642 (1997).
5. R. J. Jones, J. C. Diels, J. Jasapara, and W. Rudolph, Opt. Commun. **174,** 409 (2000).
6. A. E. Siegman, *Lasers* (University Science, Mill Valley, Calif., 1986).
7. N. Jamasbi, J.-C. Diels, and L. Sarger, J. Mod. Opt. **35,** 1891 (1988).
8. D. H. Jundt, Opt. Lett. **22,** 1553 (1997).
9. D. T. Reid, M. Padgett, C. McGowan, W. E. Sleat, and W. Sibbett, Opt. Lett. **22,** 233 (1997).
10. E. S. Wachman, D. C. Edelstein, and C. L. Tang, Opt. Lett. **15,** 136 (1990).