Doubled single-frequency Nd:YLF ring laser coupled to a passive, non-resonant cavity

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We demonstrate an original solution to obtain a single-frequency ring laser coupled to an external passive nonresonant ring cavity, which plays the role of an optical diode. This system provides more output power than systems with an intracavity unidirectional device. To the best of our knowledge, this work marks the first demonstration of a unidirectional planar ring laser at 1.3 μm. Using 12 W at 797 nm to pump a Nd:YLF laser, combined with intracavity second-harmonic generation, we achieve yields of 440 mW at 661.3 nm and 340 mW at 656.0 nm. © 2004 Optical Society of America

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1. Introduction

A. Motivation

We develop an optical clock based on the narrow two-photon transition in Ag.[1] To observe the transition with an atomic beam requires ≥500 mW at 661.3 nm, whereas, for laser cooling, ≥100 mW at 328 nm is desirable.[2] Generating the latter by frequency doubling implies ≥500 mW at 656 nm.[3] To avoid using dye lasers, we build diode-pumped Nd^{3+}-doped $YLiF_4$ lasers (hereafter Nd:YLF). We have already demonstrated standing-wave lasers with ≤750 mW single-mode power at 1.3 μm.[4,5] Here we present a novel ring laser that provides greater single-frequency output and intracavity second-harmonic generation (SHG).

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B. Traditional Methods for Achieving Unidirectional Operation

Because they avoid spatial hole burning, traveling wave lasers generally provide greater output power and better frequency stability than do their standing-wave counterparts and show identical intracavity losses. The essential difference between the two is that there is a means of ensuring unidirectional operation in the latter method. Among the different techniques to achieve this, the most frequently employed is an intracavity Faraday rotator whose rotation for one sense of propagation is compensated by the rotation due to an optically active crystal.[6] Other solutions include using a nonplanar ring cavity[7,8] or acousto-optically induced feedback.[9] The nonplanar technique is inapplicable here because Nd:YLF is birefringent, while the low gain of the medium[10] rules out the latter technique. Thus we began with a conventional ring laser containing an optical diode. The unpolarized beam from a fibre diode pump (Limo Model HLU25F200; cooled to 6 °C to emit at 797 nm where Nd:YLF has an absorption line) is collimated and focused by two doublets to a waist of 280 μm in the 0.7% Nd^{3+}-doped YLF crystal ($3 \times 3 \times 10$ mm^3). Laser operation around 1312 or 1322.6 nm is selected by the orientation of the polarization relative to the *c* axis of the crystal[10] (perpendicular for 1312 nm, parallel for 1322.6 nm). Fine wavelength tuning is achieved by use of a solid 0.1-mm thick Suprasil etalon. All mirrors are highly reflecting at 1.3 μm so as to maximize intracavity power for SHG. The optical diode consists of a Faraday rotator (FR_1) made from terbium gallium

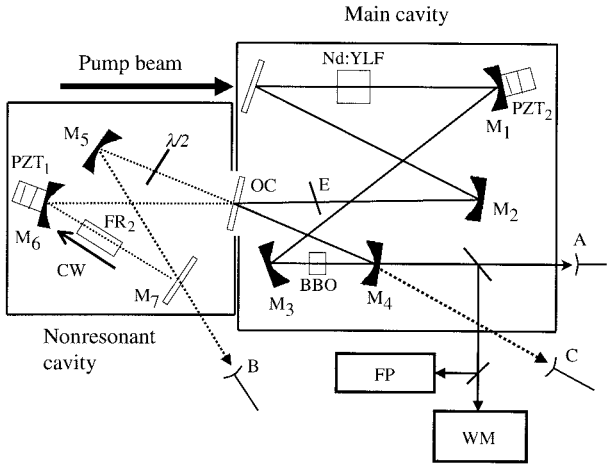

Fig. 1. Six-mirror cavity reinjected by use of a passive nonresonant cavity formed by M_5, M_6, and M_7 and the output coupler OC (T = 2%). All other mirrors have R_{max} at 1.3 μm. For SHG, a BBO crystal can be placed between M_3 and M_4. FR_2, 50° Faraday rotator; E, solid etalon (0.1 mm). Photodiodes A, main cavity clockwise power; B, external (clockwise); C, main (counterclockwise); PZT_1 and PZT_2, piezoelectric transducers; FP, Fabry–Perot spectrum analyzer; WM, wavemeter; λ/2, half-wave plate.

garnet ($Te_3Ga_5O_{12}$, known as TGG), providing a 4° rotation and a half-wave plate (λ = wavelength). Owing to absorption within the TGG crystal, even without the etalon losses, we obtained only 40 W intracavity power at 1.3 μm with 12 W of absorbed pump power at 797 nm. The intracavity power was deduced from the leakage through a high reflector (80 mW) with a transmission coefficient $T_{HR} = 0.002$. Worse still, thermal absorption of 2% (0.8 W) by FR_{11} soon caused the TGG crystal to break.

2. Nonresonant External Ring Cavity

Our solution to the above problem was to use an external passive, nonresonant cavity (henceforth referred to as NRC) to house the optically active elements (Fig. 1), with the much-lower intra-passive-cavity power traversing the rotator FR_2 to avoid thermal damage. The corresponding reduction of losses in the main cavity leads to greater power (a valuable asset for SHG). The main ring resonator is coupled to the NRC via a $T = 2\%$ output coupler that is common to both cavities. The effective optical diode is composed of a half-wave plate, antireflection coated for 1322 nm, and a TGG Faraday rotator FR_2 ($T = 80\%$ at 1.3 μm) turning the linear polarization by 50°, both in the NRC, together with the birefringent laser crystal in the main cavity. The resulting losses in the main cavity (arising from the polarization tilt and the birefringence of the Nd:YLF crystal) are higher for the counterclockwise circulating beam than for the clockwise one, a difference sufficient to impose unidirectional laser operation in the clockwise sense. The use of the external cavity to influence laser performance is described elsewhere[11–13] and entails a single injecting external mirror used to increase one-way oscillation in a three-mirror ring

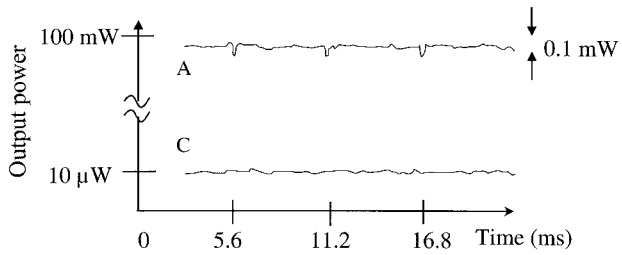

Fig. 2. Passive output powers from the main cavity as a function of time: A, clockwise; C, counterclockwise. The glitches at the 0.1% level are due to current instabilities in the pump diode power supply.

resonator. In those applications the goal was mode selection and not unidirectional operation. In fact, the quasi-unidirectional laser built in this way is susceptible to mode hops, which explains why we chose a different scheme. In our case, because we use an external ring cavity, the reinjected beam that drives the clockwise oscillation is the clockwise one; i.e. it rotates in the same sense. The laser wavelength is measured with a wavemeter (Burleigh WA-1000). The longitudinal mode of the ring laser (spacing 290 MHz) is analyzed with a 750-MHz free-spectral-range scanning confocal interferometer. Figure 2 shows that the signals are proportional to the power of the waves traveling in both directions, as recorded by the photodiodes. Note that the use of the NRC has no affect on the mode structure of the main cavity because the laser remains single frequency. This is evidenced by the fact that no mode hops were observed during several tens of seconds of free-running operation of the laser. Moreover, once the counterclockwise oscillation is nearly extinguished, a very robust unidirectional laser operation is obtained and lasts for hours. In this case the intracavity power (leakage 210 mW/$T_{HR} = 0.002$) exceeds 100 W, i.e., is 2.5 times that obtained with a conventional ring resonator.

In general, critical alignment procedures are necessary with set ups that use an external resonant cavity scheme. This results in significant power and phase changes and requires servo electronics. In our case, however, internal and external beam powers show no strong interference effects when the NRC beam reinjects the ring laser because the external cavity mode structure does not match that of the main one. Thus the alignment accuracy of the mirrors of the NRC need not be interferometric. A key parameter here is the very weak coupling between the low-finesse NRC and the ring resonator. Only $\approx 3 \times 10^{-4}$ of the ring laser intracavity power is reinjected into the ring cavity, which is sufficient to assure unidirectional operation. The observed variation of the total output power is only ≈1%. The laser beam phase is governed not only by the ring laser cavity length or electric field condition on the common mirror (either zero or a maximum) but also by the matching of the ring laser beam phase relative to that of the NRC. This effect can be seen in Fig. 3

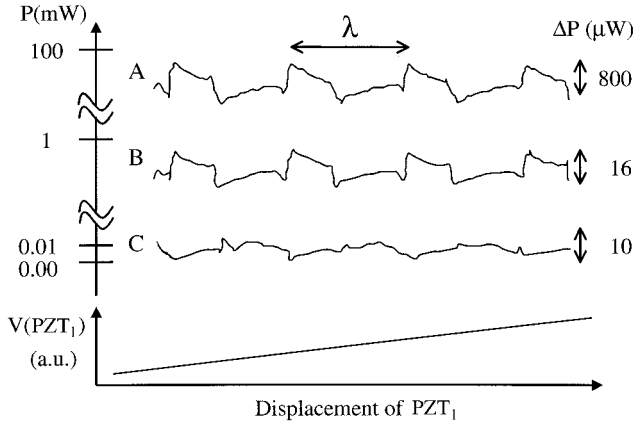

Fig. 3. Outputs from the main and reinjecting cavities as the length of the latter is varied using PZT: A, main (clockwise); B, reinjecting (clockwise); C, main (residual counterclockwise). Variations in A and B are due to polarization effects.[14] The glitches in C arise from pump diode power supply fluctuations.

in which the two signals A and B exhibit a weak periodic variation in phase as the mirror M_6 of the NRC is displaced (Fig. 1). The small ac variation of the detected power (A, B) with a period of λ is evidence of the residual weak interaction between the phase-matched beams. Figure 3 shows the NRC wave traveling in the clockwise direction (B) and the waves in the ring laser traveling in both clockwise (A) and counterclockwise directions (C) as we scan the NRC length over a few wavelengths by using the piezoelectric transducer PZT_1. The rather weak signal due to the counterclockwise beam (signal C) has the ac part of its phase shifted by ≈180° relative to the signals due to the clockwise beams (A and B). Moreover, this counterclockwise power is very small compared with that observed in the other external coupling scheme used to enhance clockwise operation; i.e., the one using a single external mirror.[11,12,13] In our case, because the counterclockwise beam circulating in the ring laser cavity has a power 10^4 times weaker than the clockwise one, the laser can be deemed unidirectional. For optimal performance one could always servo lock the laser output power close to its maximum value (i.e., the value that corresponds to the minimum counterclockwise power) and derive the required error signal from the two outputs A and C of Fig. 1.

3. Frequency Doubling

The reduction of losses in the main cavity leads to increased fundamental power, a great advantage for intracavity frequency doubling. To perform SHG, we insert between mirrors M_3 and M_4 a type-I β-BaB_2O_4 frequency-doubling crystal, 7 mm long and with both faces antireflection coated at 1322 and 661 nm. The average spot size in the crystal is 45 μm. With 12.0(2) W of absorbed pump power at 797 nm, the maximum output powers at 661.3, 656.0 and 660.5 nm (the gain maximum) are 440(10), 340(10), and 660(10) mW, respectively (see Fig. 4).

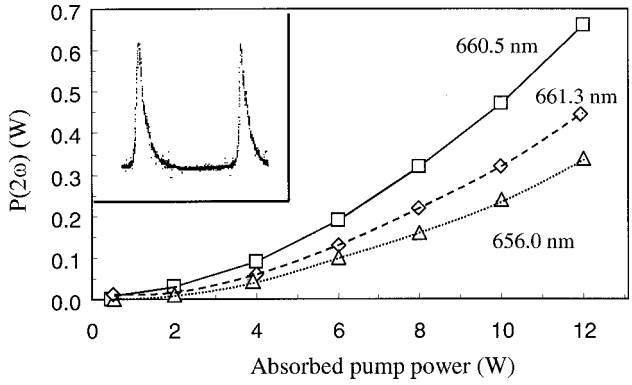

Fig. 4. SHG yields [P(2ω)] versus pump power at λ_p = 797 nm. Inset: Fabry–Perot transmission at 1.322 μm, confirming single-mode generation of 661.3 nm.

By contrast, using a conventional ring laser with an intracavity TGG Faraday rotator, even without the losses of the solid etalon, we obtained only 90(10) mW at 660.5 nm under identical pumping conditions. Moreover, intracavity SHG enhances intensity and frequency stability, as explained elsewhere.[15] To check the continuity of single-frequency operation as the wavelength is scanned, we vary the ring laser cavity length by a few micrometers (corresponding to 2.5 GHz) by ramping the voltage on PZT_2.

4. Conclusion

We have presented a diode-pumped unidirectional Nd:YLF ring laser coupled to a nonresonant ring cavity. This novel system yields a higher intracavity power at a wavelength of 1.3 μm than does a conventional ring laser containing a TGG optical diode under identical pumping conditions. Most important, the intensity instabilities from the external nonresonant cavity have no discernable effect upon the laser frequency, at once making the device a useable, practical tool. Nevertheless, the dynamic intensity and phase behavior of these configuration lasers merit further investigation.

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