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Generation of 20 mW of blue laser radiation from a diode-pumped sum-frequency laser

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Resonant intracavity sum-frequency mixing of a diode-pumped Nd:YAG laser and a 100 mW single stripe laser diode, has been used to generate a measured output power of 20 mW of blue laser radiation at 459 nm. This represents a total conversion efficiency of approximately 68% of the single stripe laser diode power incident on the cavity. The laser was also demonstrated to operate over a tuning range of 12 nm via angle tuning of the nonlinear crystal.

An all solid-state, diode-pumped source of laser radiation in the blue spectral region is of significant interest for potential applications such as optical data storage, undersea communications, and laser displays. Approaches based on resonantly enhanced nonlinear frequency conversion of infrared radiation from laser diodes have been extensively pursued over the last few years. Direct frequency doubling of GaAlAs laser diode radiation in $KNbO_3$[1–3] is well suited to the 420–430 nm spectral range, where laser diode sources are commercially available. Longer wavelengths are more readily generated by mixing the most common diode-pumped solid state laser output, Nd:YAG at 1064 nm, with the most commonly available laser diode outputs, at 800–860 nm, to produce 455–475 nm radiation, using $KTiOPO_4$ (KTP)[4-6] or $KNbO_3$ (Refs. 7 and 8) as the nonlinear medium. Efficient coupling of the laser diode output to the fundamental mode of the external resonant cavity demands a high quality Gaussian beam which generally necessitates the use of a single stripe, index guided laser diode. These lasers are presently limited in power to ~ 150 mW cw, so it is important to obtain high conversion efficiency of this output. For sum-frequency generation, this is best achieved by resonantly enhancing both input wavelengths. In previous work,[5] a single-stripe laser diode and the technique of resonant pumping were used to achieve doubly resonant sum-frequency generation. This resulted in a significant fraction of the high quality diode output being used to pump the Nd:YAG laser, limiting blue output power to $\leqslant 2.5$ mW. More recently, Risk and Kozlovsky[6] simultaneously resonated an 809 nm single stripe laser diode and a separate, diode-pumped Nd:YAG laser in an external monolithic KTP resonator to obtain 4 mW of blue output. To produce a steady state output in this scheme, both the laser diode and Nd:YAG laser need to be kept coincident with a resonance frequency of the external cavity. By placing the KTP crystal inside the Nd:YAG laser cavity, which also serves as an external resonator for the 809 nm laser diode, the pump light at 1064 nm is automatically on resonance and it is only necessary to control the frequency of the single stripe laser diode. The need for isolators and mode-matching optics in the Nd:YAG beam, with their attendant insertion losses, is also eliminated. In this letter we describe a sum-frequency laser based on this approach, using a high power, broad area laser diode to pump the Nd:YAG laser containing a KTP crystal intracavity, and a second, index guided, single stripe laser which is mode matched to the laser cavity for resonant intracavity sum-frequency mixing.

For this work, we chose KTP as the nonlinear medium. Fortuitously, KTP has a room temperature, noncritical, type II phase match for sum-frequency mixing of 1064 and 809 nm inputs to produce 459 nm blue light.[4] $KNbO_3$ could also be used as the nonlinear material in the present system, if the input polarizations were made parallel rather than orthogonal, to accommodate the type I phase match in this material. $KNbO_3$ (Ref. 7) has a figure of merit for resonant nonlinear conversion, $(d/n)_2$, which is ~ 60 times larger than that of KTP[9] and it maybe more resistant to optical damage,[10] but it is less attractive from a device engineering standpoint. The angular and wavelength acceptances for a 6 mm length of KTP[4] are $\sim 6°$ and ~ 2 nm compared to $\sim 1.8°$ and ~ 0.13 nm for $KNbO_3$.[7] The phase match in KTP is almost completely independent of temperature,[4] while the strong temperature dependence of refractive indices in $KNbO_3$ (Ref. 7) requires temperatures control to 0.1 °C or better. The noncritical phase match temperature for this interaction in $KNbO_3$, which is ~ 158 °C, is high enough that thermally induced depoling of the crystal is a concern. KTP is also more readily available, more mechanically robust and more easily fabricated than $KNbO_3$.

Our experimental arrangement is shown in Fig. 1. A broad area 1 W semiconductor laser diode (Spectra Diode Labs 2462) was used to pump a Nd:YAG laser. The cavity was based on a folded resonator design to allow for a second input. A Brewster plate was used to fix the polarization of the 1064 nm radiation and a thin fused silica plate, mounted normal to the cavity TEM_{00} mode, was coated to act as a cavity end mirror for the 809 nm mixing source (M_1). This had an antireflection coating at 1064 nm on one side and approximately 20% reflectivity at this wavelength from the other surface due to the high reflectivity coating at 809 nm. Since the plate was aligned normal to

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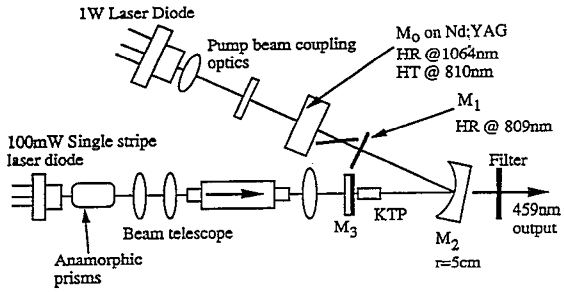

FIG. 1. Schematic diagram of the experimental arrangement for the two-input sum-frequency laser.

the beam it simply formed a weak intracavity etalon with the end mirrors of the cavity. Ideally this coating would be a dual wavelength coating, highly reflecting for 809 nm and antireflection for 1064 nm. The curved mirror (M_2) was coated for high reflectivity at both wavelengths and had a radius of curvature of 5 cm. Finally the flat end mirror (M_3) was highly reflecting at 1064 nm and had a transmission of approximately 15% at 809 nm. The physical distance between M_0 and M_2 was ≈ 8 cm, $M_1-M_2\approx 5$ cm and $M_2-M_3\approx 3$ cm. An antireflection coated KTP crystal cut with $\theta=\phi=90°$ and length 6 mm was mounted close to the waist located on the flat end mirror. A second, 100 mW single stripe laser diode (Spectra Diode Labs model 5412), temperature tuned to 809 nm, was collimated and mode matched into this cavity through the flat end mirror. Two optical isolators were required between the diode laser and cavity to prevent backreflection induced instabilities. This arrangement allowed reasonably efficient operation of the Nd:YAG laser in a fixed polarization state and also provided a subcavity between M_1 and M_3 to resonate the orthogonally polarized 809 nm radiation. There was some astigmatism due to the off axis curved mirror and a slight size mismatch between the cavity modes of the two wavelengths. We calculated the spot sizes on the flat end mirror, M_3, to be approximately 36×28 μm for the 1064 nm beam, and 39×30 μm for the 809 nm beam.

For efficient coupling of the single stripe laser diode to the cavity, the mirror transmission of M_3 must be "impedance matched" to the cavity losses.[11] The value of 15% quoted above was close to that initially estimated from a calculation using the theory of Boyd and Klienmann (BK).[12] The conversion efficiency to the sum frequency η in the limit of low pump power conversion (P_1) is given by

$$\eta=\frac{P_3}{P_2}=\frac{4\omega_1\omega_2\omega_3}{\pi\epsilon_0 c^4 n_3^2}\, d^2 LhP_1, \qquad (1)$$

where ω is angular frequency, d the effective nonlinear coefficient, L the crystal length, n the refractive index of the KTP, and h is the BK focusing parameter. The subscripts 1, 2, 3 refer to the 1064, 809, and 459 nm wavelengths, respectively. In our case of a nearly hemispherical focusing geometry,[13] we estimated $h\approx 0.25$ and the relevant nonlinear coefficient is d_{15}. The power enhancement of the 809 nm radiation incident on the cavity, P_{inc}, is given by the following:

$$P_2=\frac{M(1-R_3)}{\{1-[R_1R_2R_3(1-\eta)^2(1-l_p)^2]^{1/2}\}^2}\, P_{inc}, \qquad (2)$$

where R_i is the reflectivity of the mirrors, l_p the single pass parasitic losses within the cavity, and M a mode-matching parameter (≈ 0.9). The reflectivity of the input coupling mirror for optimum impedance matching is then given by $R_3=R_1R_2(1-\eta)^2(1-l_p)^2$. Using the published value for d_{15} of 6.1 pm/V (Ref. 14) we calculated a value of 20% for the transmission of M_3 at 809 nm assuming an intracavity pump power of $P_1\approx 20$ W. However, Vanherzeele and Bierlein[9] have recently published revised values for the magnitude of the nonlinear-optical coefficients in KTP and in particular, measure the d_{15} coefficient to be approximately a factor of 3 lower than previously reported, i.e., $d_{15}\approx 2$ pm/V. If this value is used in Eq. (1), we obtain an optimum transmission for M_3 of approximately 3.5%. This difference implies that with our mirror transmission of 15%, for $P_1=20$ W, the cavity is substantially over coupled. As seen below, with the new value for d_{15}, the theory outlined above accounts well for the observed dependence of the generated sum-frequency power on intracavity pump power at 1064 nm.

Due to the insertion loss of the isolators, the maximum power incident upon the cavity from the single stripe laser diode was ≈ 65 mW and the maximum intracavity power at 1064 nm was inferred from measurements of the power transmitted through M_2, to be approximately 54 W. This produced a useful output power of 20 mW at 459 nm. The transmission of M_2 was approximately 90% at this wavelength and so the generated blue power within the cavity was ≈ 22 mW. The KTP crystal was apparently nonuniform across its aperture, as the circulating powers at both 809 and 1064 nm (and hence the 459 nm output power) varied somewhat as the crystal was translated across the beam. The power quoted above represented the optimum KTP position. A Pound–Drever (FM sideband) locking scheme was employed to keep the laser diode matched to a cavity resonance. Figure 2 is a plot of the generated sum-frequency power within the cavity (i.e., corrected for the transmission of the filter and curved mirror) as a function of the intracavity pump power at 1064 nm. The curve (a) was calculated using Eqs. (1) and (2) above with the mirror transmission $T_3=15\%$ and with $d_{15}=2$ pm/V. Given that the crystal was not located exactly at the cavity waist and the uncertainty of other factors used in the calculation (e.g., spot sizes and extent of mode mismatch) it can be seen that the experimental results follow the calculated curve reasonably well. For an intracavity pump power ≈ 20 W the cavity is indeed over coupled and the sum frequency power produced was approximately half of what could be expected with the optimum reflectivity of M_3 [indicated by curve (b)]. The highest actual pump power was on the order of 50 W and in this case the blue power generated is only a few milliwatts below that expected for

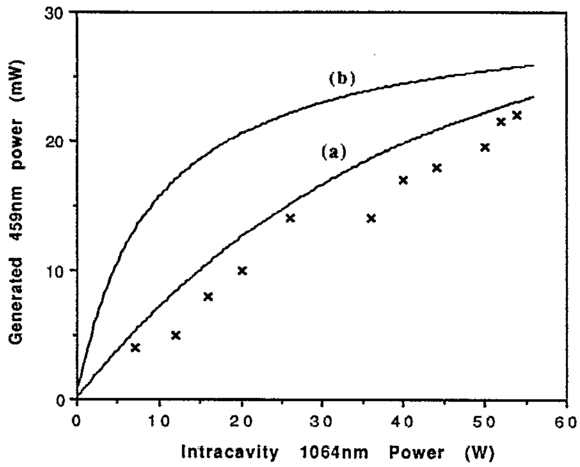

FIG. 2. The output power at 459 nm (P_3) as a function of the intracavity pump power at 1064 nm (P_1). Curve (a) is a theoretical curve for our experimental conditions with $T_3 = 15\%$ and a curve (b) is for the case of optimum input coupling (impedance matching) at each value of pump power.

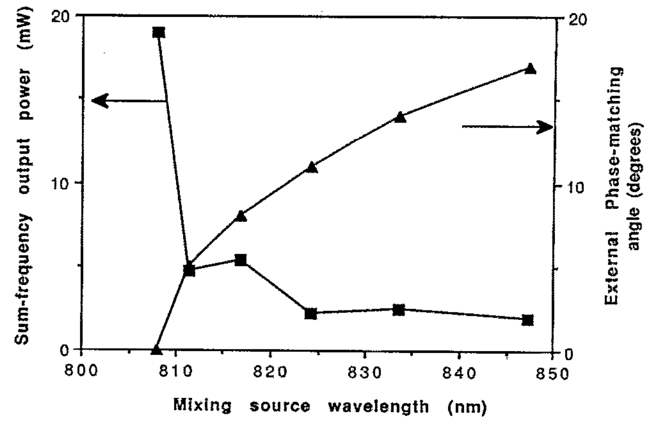

FIG. 3. Tuning curve obtained with a Ti:sapphire laser as the mixing source and by angle tuning of the KTP (the solid lines are simply an aid to the eye). All points are for an incident mixing source power of 65 mW.

optimum coupling, even though the mirror transmission used in the experiment was above twice the optimum value ($T_{3\,\mathrm{opt}} \approx 7.5\%$).

The standing wave cavity also produced blue light propagating back towards the mixing source and by inserting a dichroic mirror between the isolator and mode-matching lens, the blue power emitted in this direction was measured to be similar to that exiting the curved mirror. This implies the total maximum power produced was ≈ 44 mW which represents a conversion factor of 68% of the single stripe laser diode power incident on the cavity. Although the total optical to optical efficiency is much lower (approximately 4%) since a 1 W laser diode is used to pump the Nd:YAG laser, the beam from this laser is non-diffraction limited and is not practically useful for direct nonlinear frequency conversion.

We were able to obtain tunability of this device via angle tuning of the KTP and substituting a single frequency Ti:Al_2O_3 laser for the single stripe laser diode. The tuning curve is shown in Fig. 3 and shows a tuning range over approximately 40 nm of the mixing source, limited mainly by the aperture of the KTP crystal. No locking scheme was used to keep the Ti:sapphire laser frequency locked to a cavity resonance and so drifts in the frequency of the laser or cavity caused the output to exhibit a large modulation at frequencies of a few kilohertz. Thus the power measurements recorded in Fig. 3 are averaged values and the true steady state values would be somewhat higher. The sharp drop in sum-frequency output power when tuned away from noncritical phase matching, is mostly due to increased cavity losses which caused a reduction of the intracavity 1064 nm pump power to ≈ 10 W as the KTP was rotated off axis. Lower conversion efficiencies would also be expected as the phase-matching angle increases, due to the effect of double refraction or beam walk-off.

In summary we have demonstrated the production of 20 mW of blue laser radiation at 459 nm from a diode pumped sum-frequency laser. This represents a total conversion efficiency of approximately 68% of the power incident on the cavity from the single stripe laser diode. The output power is equal to that obtained by direct frequency doubling in $KNbO_3$ at equivalent single-stripe laser diode incident power of 65 mW.[3] The device is compact, $< 30 \times 10$ cm^2, except for the ~ 50 cm path length required in the single-stripe laser beam path to accommodate the beam telescope and optical isolators. Adaptation of a unidirectional ring geometry would produce the blue radiation in a single output beam and would enable the elimination of the beam telescope and optical isolators, resulting in a more compact design with the possibility of optically locking the diode to the cavity. Finally, the laser was operated over the wavelength range 459 to 471 nm by angle tuning of the KTP. This resonant, intracavity technique may be applied to other nonlinear materials and diode laser/gain media combinations for efficient generation of other sum-frequency wavelengths of interest.

[1] G. J. Dixon, C. E. Tanner, and C. E. Wiemann, Postdeadline Papers, OSA Annual Meeting 1988 (Optical Society of America, Washington, DC, 1988).
[2] L. Goldberg and M. K. Chun, Appl. Phys. Lett. **55**, 218 (1989).
[3] W. J. Kozlovsky, W. Lenth, E. E. Latta, A. Moser, and G. L. Bona, Appl. Phys. Lett. **56**, 2291 (1990).
[4] J.-C. Baumert, F. M. Schellenberg, W. Lenth, W. P. Risk, and G. C. Bjorklund, Appl. Phys. Lett. **51**, 2192 (1987).
[5] P. N. Kean and G. J. Dixon, Opt. Lett. **17**, 127 (1992).
[6] W. P. Risk and W. J. Kozlovsky, Opt. Lett. **17**, 707 (1992).
[7] J.-C. Baumert and P. Günter, Appl. Phys. Lett. **50**, 554 (1987).
[8] L. Goldberg, M. K. Chun, I. N. Duling III, and T. F. Carruthers, Appl. Phys. Lett. **56**, 2071 (1990).
[9] H. Vanherzeele and J. D. Bierlein, Opt. Lett. **17**, 982 (1992).
[10] W. Seelert, P. Kortz, D. Rytz, B. Zysset, D. Ellgehausen, and G. Mizell, Compact Blue-Green Lasers, 1992 Technical Digest Series, Vol. 6 (Optical Society of America, Washington, DC, 1992), p. 72.
[11] W. J. Kozlovsky, C. D. Nabors, and R. L. Byer, IEEE J. Quantum Electron. **24**, 913 (1988).
[12] G. D. Boyd and D. A. Kleinman, J. Appl. Phys. **39**, 3597 (1968).
[13] G. D. Boyd and F. R. Nash, J. Appl. Phys. **42**, 2815 (1971).
[14] J. D. Bierlein and H. Vanherzeele, J. Opt. Soc. Am. B **6**, 622 (1989).