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HIGH-EFFICIENCY FREQUENCY DOUBLING FOR THE PRODUCTION OF 780 NM LIGHT

Steven Peil, Scott Crane, and Christopher R. Ekstrom
U. S. Naval Observatory, Washington, D. C.

Abstract – **We are developing a source of 780 nm light for use in rubidium atomic clocks by frequency doubling telecom-laser light in a periodically poled lithium niobate waveguide. A single-pass doubling efficiency of 70% and 780 nm power of 100 mW have been demonstrated.**

I. INTRODUCTION

ATOMIC fountain clocks require hundreds of milliwatts of laser light for cooling and manipulation of atoms. Diode lasers have often been used for these systems, but with the focus on the telecommunications wavelength band, ~1500 – 1600 nm, the availability of reliable high-power diodes and amplifier chips at wavelengths useful for atomic laser-cooling applications has diminished. The latest generation of Ti:sapphire laser offers high power and more reliability than in the past, but it is expensive and the entire system, including pump laser and fluid cooling loop, is not very compact and not easily used for multi-year operation.[1]

Given these obstacles, it is desirable to find a source of laser light for atomic clocks that relies on more readily available and compact components. The telecommunications spectrum of 1500 – 1600 nm includes wavelengths that are twice the wavelengths of the laser cooling transitions in rubidium (i.e., the *D*1 line at 795 nm and the *D*2 line at 780 nm). Frequency doubling these parts of the telecom spectrum can thus serve as a laser source for rubidium systems, opening up the vast array of resources developed for the telecom industry to the scientific community working with rubidium.

We have developed a source of 780 nm laser light with moderate power by frequency doubling the amplified output of a 1560 nm telecom laser with a periodically poled lithium niobate (PPLN) waveguide, shown in Fig. 1. We use a fiber-coupled, distributed-feedback (DFB) semiconductor laser at 1560.61 nm,[2] in the C-band of the telecom spectrum. DFB lasers are readily available, typically have linewidths of several MHz, are intrinsically single-mode, and generate outputs of 1 – 40 mW. We boost the laser output to as much as 1 W with a polarization-maintaining erbium-doped fiber amplifier. A fraction of this light is successfully coupled into a PPLN waveguide for frequency doubling.

II. FREQUENCY DOUBLING WITH PPLN

Frequency doubling is becoming more routine due to the emergence of periodic poling in nonlinear materials, in which the sign of the nonlinear coefficient is inverted at regular intervals.[3] This is a general technique of increasing the interaction length between the fundamental and second harmonic waves (by quasi-phase matching [1-3]) that can be tailored to many different input wavelengths by altering the poling period. PPLN is popular for frequency doubling because of lithium niobate's large nonlinearity.

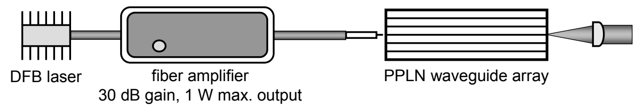

Figure 1: Schematic of apparatus used to generate 780 nm light from a telecom laser.

In addition to the advantages provided by PPLN, waveguide fabrication in the crystal offers dramatic improvements in doubling efficiency [4]. The waveguide provides tight confinement of the fundamental beam over the entire length of the crystal, which increases the average intensity over the length, and therefore the doubling efficiency, compared to the bulk material. In our system we have an array of waveguides on a single PPLN crystal, with individual waveguides having one of four different poling periods. A given poling period enables only one specific frequency to be doubled; changing the temperature of the crystal changes the poling period and thus the doubled frequency. For our one input frequency, we can double at four different temperatures. This allows us to look at various waveguide temperatures for photorefractive effects, which can limit the amount of doubled light generated and can be mitigated by heating the PPLN.

Our waveguides are 5 cm long and have a rated unit doubling efficiency of ~80%/(W·cm^2) [5]. The four different poling periods enable us to double at temperatures of 30, 75, 110, and 140 °C. An example of the doubling performance versus input wavelength of a waveguide at 110 °C is shown in Fig. 2. Our failure to observe the expected sinc^2 shape [3] is probably due to imperfect uniformity of heating along the length of the waveguide.

III. MEASUREMENTS OF SYSTEM PERFORMANCE

A. Doubling Performance

We measure the doubling efficiency of a waveguide by measuring both the 1560 nm and 780 nm powers after the crystal (after the lens in Fig. 1). These powers are divided

[1] For example, a Ti:sapphire laser is not easily integrated into a space clock.

[2] 1560.61 nm is the closest telecom wavelength to 1560.48 nm. DFB lasers typically have a temperature-tuning range of 1–2 nm.

[3] More generally, the nonlinear coefficient is modulated periodically.

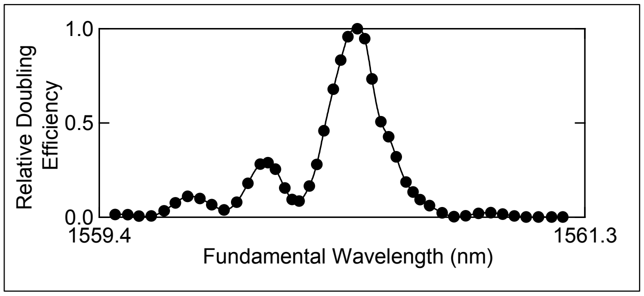

Figure 2 : Wavelength tuning curve of one of our waveguides at 110 °C. This plot is obtained by measuring the doubling efficiency as we temperature tune the wavelength of the input laser.

by the transmittance of the uncoated waveguide output, 0.86 for lithium niobate, to get the powers at the end of the waveguide. We neglect the propagation loss in the waveguide for both the fundamental and the second harmonic and define the doubling efficiency as the 780 nm power at the end of the waveguide divided by the sum of the 780 nm and 1560 nm powers at that point. Results are shown in Fig. 3. The doubling efficiency, shown in the bottom graph, is observed to level off at 70%. The doubling efficiency necessarily saturates as depletion of fundamental power approaches 100%. Saturating below 100% could be due to imperfect quasi-phase matching along the length of the waveguide from fabrication imperfections, heating non-uniformities, or photorefractive effects.

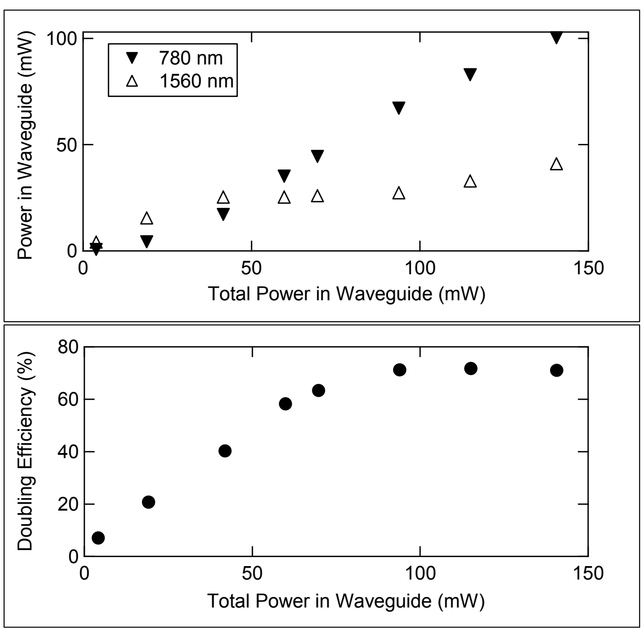

Figure 3 : Doubling performance of PPLN waveguide at 110 °C. The top graph shows fundamental and second harmonic powers at the end of the waveguide versus the sum of the two. The bottom graph shows the doubling efficiency versus total power in the waveguide.

The maximum total power in the waveguide in Fig. 3 is much lower than the 1 W available because we only get about 15% of the amplifier output into the waveguide with butt-coupling. This poor coupling efficiency is a major problem that needs to be remedied. We have seen that professionally pigtailing a fiber to the input of the waveguide increases the coupling efficiency to about 35%. This could possibly be further improved by implementing a tapered fiber or waveguide. Alternatively, focusing into the waveguide may be an improvement over our current setup.

B. Photorefractive Effects

Photorefractive effects induced by the light in the waveguide can ultimately limit the 780 nm output power as the total intensity is increased. This problem can be mitigated by raising the temperature of the PPLN crystal; operating temperatures between 100 and 200 °C for frequency doubling are not uncommon. In Fig. 4 we plot the 780 nm output for 100 mW of total power in the waveguide at our four different doubling temperatures. The first two points show the *maximum* 780 nm powers that can be sustained at 30 °C and 75 °C. At the higher temperatures of 110 °C and 140 °C, the 780 nm output is not limited by photorefractive effects, and thus we expect to be able to achieve higher outputs from these waveguides as we increase coupling efficiency. The beneficial effect of increasing the waveguide temperature is dramatic.

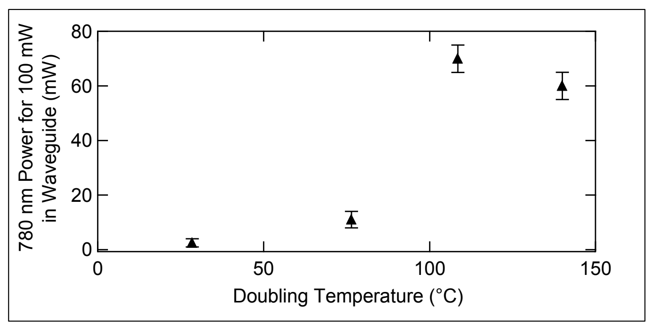

Figure 4 : Plot showing photorefractive limits at low temperatures. The first two points represent the maximum attainable 780 nm power at these temperatures. At the two highest temperatures, the output is not limited by photorefractive effects. The difference between the 110 °C and 140 °C values is due to a difference in doubling efficiency for these waveguides.

C. Laser Performance

We use the 780 nm light from this system to demonstrate a saturated-absorption spectrum of rubidium *D*2 lines, shown in Fig. 5. The first two sets of transitions of the familiar ^{85}Rb – ^{87}Rb spectrum show individual Doppler-free peaks, each of which is about 6 MHz (FWHM) wide. While we have not made a careful linewidth measurement, this preliminary demonstration suggests the spectral properties of the DFB laser should be good enough for laser cooling applications. The inset of Fig. 5 shows the entire ~7 GHz spectrum, over which the DFB laser can easily be scanned single mode.

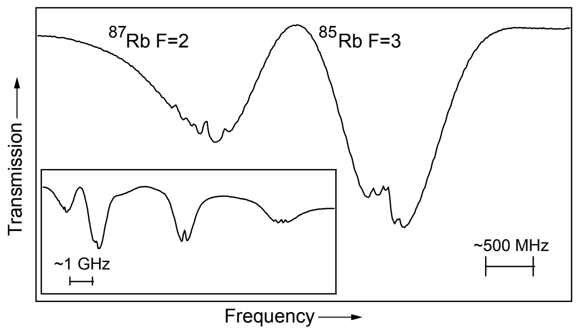

Figure 5 : Portion of standard 780 nm rubidium spectrum, showing ^{87}Rb F=2 ground-state and ^{85}Rb F=3 ground-state transitions. Inset : Entire 7 GHz spectrum.

IV. FUTURE DIRECTIONS

We would like to achieve a 780 nm output power on the order of 0.5 – 1.0 W. This will require getting more 1560 nm light into the waveguide, which could be achieved by a combination of higher 1560 nm power and better coupling efficiency. Higher crystal temperatures may prove necessary as we increase the intensity in the waveguide.

While a DFB laser source may be fine for this system, there are other 1560 nm sources that should have even narrower linewidths, including fiber lasers and miniature external-cavity diode lasers, making this technique more broadly applicable. Additionally, there are now fiber lasers and amplifiers that can produce on the order of 10 W of output. At these higher 1560 nm powers, it should be possible to generate on the order of 1 W of 780 nm light even with limited coupling efficiency. This could result in a 10 W pumped, 1 W output system, similar to a Ti:sapphire laser, but in an air-cooled, compact package at a fraction of the price.

We note that work at the Jet Propulsion Lab [6] has demonstrated a single-pass efficiency for generating 780 nm light in bulk PPLN comparable to our combined (coupling × doubling) efficiency. A possible advantage to the bulk system is that the fundamental light that is not converted can be used in a second pass (or a build-up cavity), whereas in our case the light that is not coupled into the waveguide is lost.

V. CONCLUSION

We have demonstrated the application of technology available for telecommunications to the generation of laser light for rubidium systems. Using a PPLN waveguide for frequency doubling of 1560 nm light, we have observed 70% doubling efficiency and a second harmonic power of 100 mW. It is likely that we will be able to improve on the 780 nm output power in order to make this technique more broadly applicable.

ACKNOWLEDGMENT

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[5] HC Photonics Corporation, Hsinchu, Taiwan. USNO does not endorse any commercial product, nor does USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

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