SUM FREQUENCY GENERATION OF CW 194 nm RADIATION IN POTASSIUM PENTABORATE

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ABSTRACT

Narrowband, tunable cw radiation in the 194 nm region has been produced by sum frequency mixing in a potassium pentaborate (KB5) crystal. The input wavelengths required for 90° phase-matched sum frequency mixing (SFM) are approximately 257 nm and 792 nm. The tunable 792 nm radiation was obtained from a cw dye laser. The 257 nm radiation was obtained by frequency doubling the output of a cw argon ion laser in an ammonium dihydrogen phosphate (ADP) crystal. It is estimated that several microwatts of 194 nm radiation in a bandwidth of less than 10 MHz can be produced when all operating conditions are optimized.

INTRODUCTION

Proposals have been made for microwave and optical frequency standards based on transitions of mercury ions stored in Penning traps.[1] These standards have the potential of achieving absolute accuracies of 1 part in 10^{15} or greater, better than any standards now in existence. These proposals require a narrowband cw source of radiation tunable around the first resonance line of the ion (194.23 nm), for radiation-pressure cooling[2,3] and optical pumping.[1,4] (The wavelengths referred to in this paper are all vacuum wavelengths.) For optimum cooling, the frequency bandwidth and stability of the source must be less than the natural linewidth of the resonance line of the ion (about 70 MHz). The minimum cw power required is about 1 μW.

Our method for producing 194 nm radiation is to sum frequency mix the 257 nm second harmonic, generated in an ADP crystal, of the output of a cw 514.7 nm argon ion laser with the output of a tunable cw dye laser in the 792 nm region in a KB5 crystal (see Fig. 1). Previously, Stickel and Dunning,[5] using pulsed dye lasers, have generated coherent radiation tunable between 185 nm and 217 nm by SFM in KB5. With cw lasers, the frequency stability and bandwidth requirements can easily be satisfied. Meeting the minimum power requirement is feasible, provided that resonant cavities are used to enhance the efficiencies of the frequency doubling and mixing stages.[6]

ISSN:0094-243X/82/900485-06$3.00

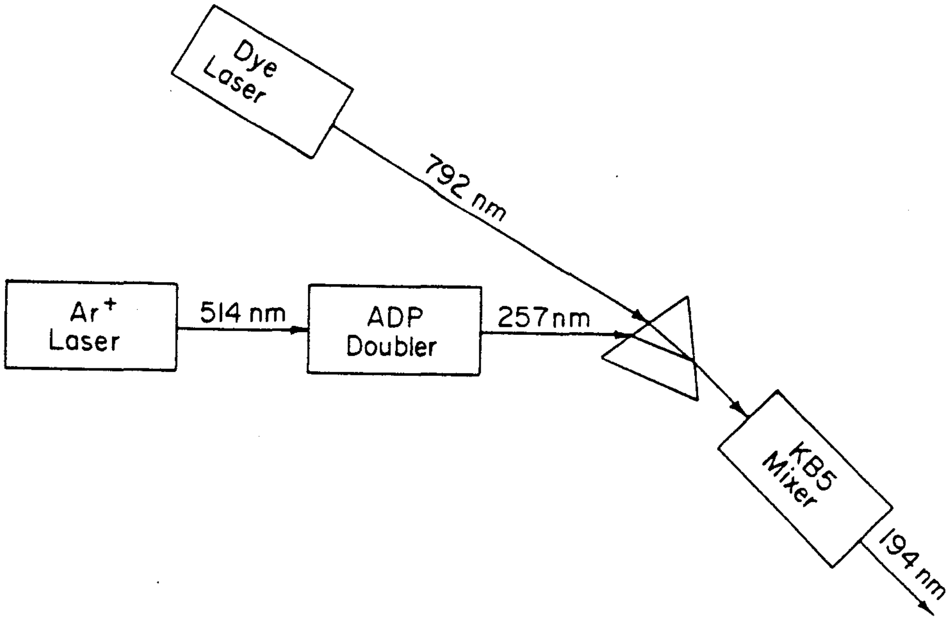

Figure 1. Technique for cw generation of 194 nm.

ADP DOUBLING STAGE

The ring cavity frequency doubler is shown in Fig. 2. The cavity is servo controlled to resonate at the fundamental wavelength (514.7 nm) in order to enhance the second harmonic generation (SHG) in the ADP crystal. A similar method has recently been used by Brieger et. al.[7] to frequency double the output of a dye laser in an ammonium dihydrogen arsenate (ADA) crystal. In our experiments, single mode operation of the argon ion laser was obtained by inserting an etalon into the cavity.

For 90° phase-matched SHG, which gives the highest efficiency, the ADP crystal must be cooled to about -11°C. Dry nitrogen was flowed across the crystal faces to prevent condensation of water. A sealed cell with Brewster windows, filled with argon or helium, was also tried, with good results. The ring cavity was servo controlled by using the polarization method of Hansch and Couillaud[8] to detect a deviation from the resonance condition. A dichroic beamsplitter was used to extract the 257 nm from the cavity. Further details of the cavity design will be given in a later publication.[9]

As much as 80 mW of steady cw second harmonic output has been observed. The circulating power inside the ring cavity was 12.5 times higher than the 2 W power of the argon ion laser. This ratio was determined by measuring the 514.7 nm power leaking through one of the cavity mirrors when the input coupling mirror was in place and when it was removed. The crystal used was 5.5 cm long. This output is considerably below that which would be expected from extrapolation of the results obtained at low input powers.

This is presumably due to absorption of the fundamental and second harmonic in the crystal, which causes a temperature gradient and disturbs the phase matching. This effect has been discussed by Okada and Ieiri.[10]

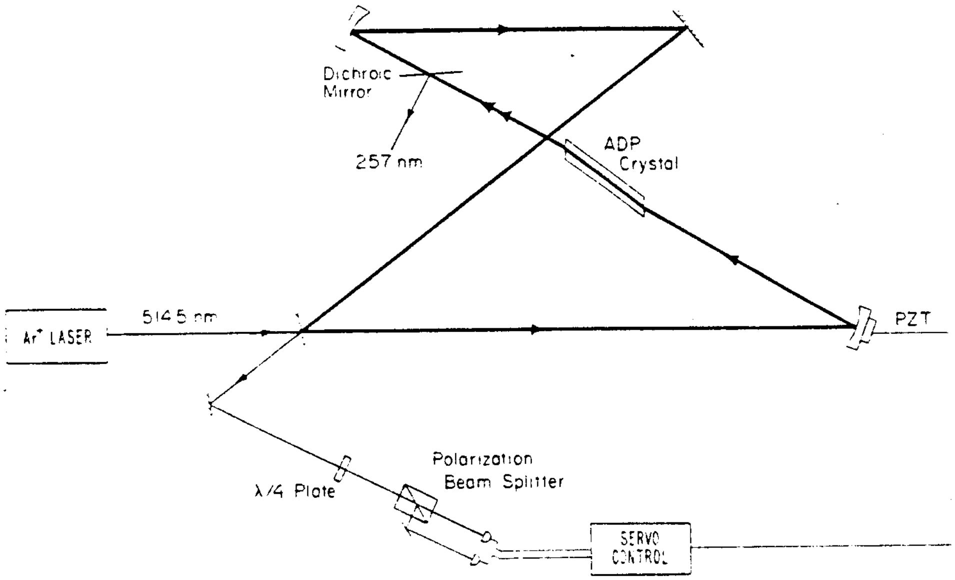

Figure 2. ADP ring cavity frequency doubler.

KB5 MIXING STAGE

The ring cavity sum frequency mixer is shown in Fig. 3. The cavity is servo controlled to resonate at the wavelength of the dye laser (about 792 nm) by the same method that was used for the doubling cavity. The KB5 crystal is 3 cm long. The 257 nm radiation is injected into the ring with a dichroic mirror and the 194 nm radiation is extracted with another dichroic mirror. The ratio of the circulating 792 power inside the cavity to the output of the dye laser has been measured to be about seven. The single-mode ring dye laser is pumped by a krypton ion laser and uses LD700 dye.

The experiments are still in progress, and so far the only SFM results have been obtained using a 1 cm KB5 crystal and without the mixing cavity. The 194 nm output was separated with a fused silica prism and detected with a photomultiplier tube. The absolute intensity was not known very accurately, but was estimated to be approximately 1 nW. The input powers, measured at the entrance window of the crystal housing, were approximately 10 mW at 257 nm and approximately 100 mW at 792 nm. For these experiments, the dye laser was multimode, with a bandwidth of about 1 cm^{-1}.

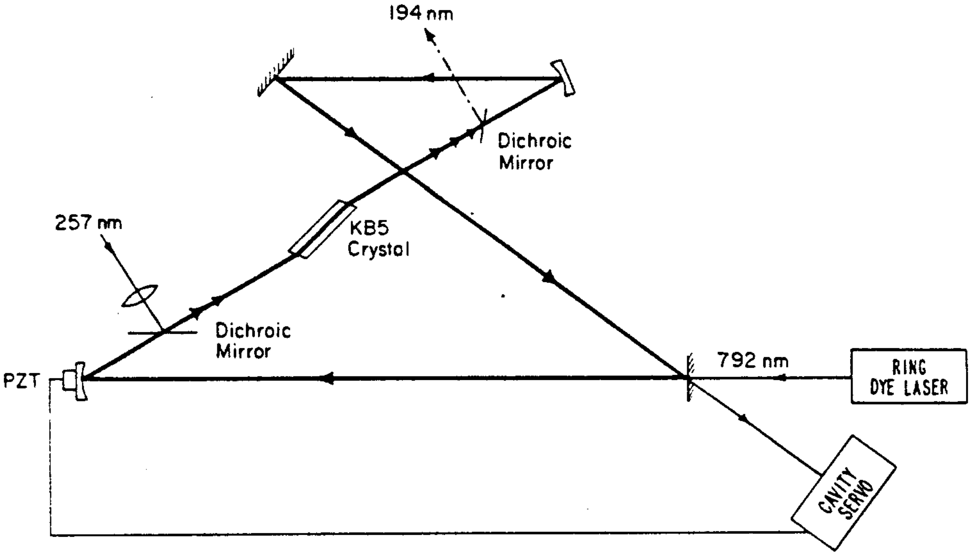

Figure 3. KB5 ring cavity frequency mixer.

Figure 4 shows the propagation angle for the input beams in the a-b plane, relative to the b axis, versus the wavelength for which phase-matched SFM occurs. The crosses represent our data; the solid curve is calculated from previously published indices of refraction.[11]

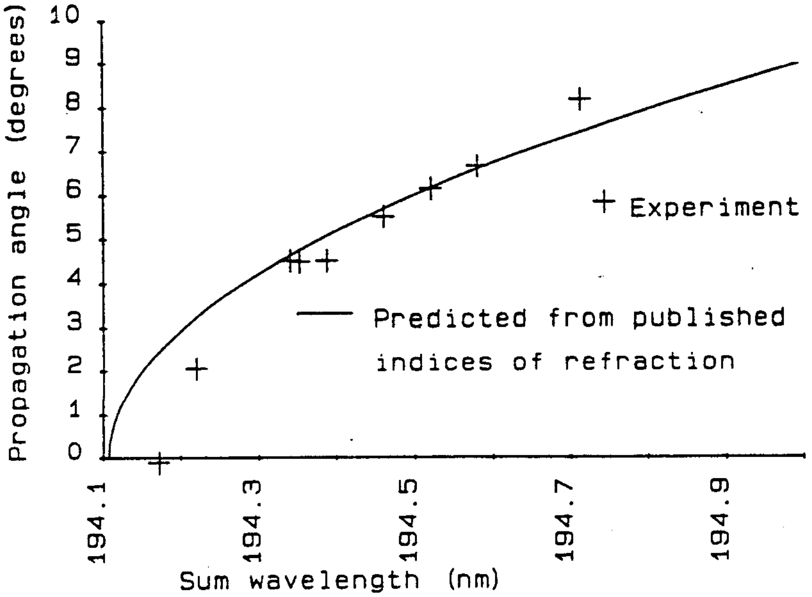

Figure 4. Angle tuning curve for KB5 SFM.

Figure 5 shows the wavelength for which 90° phase-matched SFM occurs, as a function of temperature. The greatest conversion efficiency occurs when the 90° condition is met (propagation along the b axis). The crosses represent our experimental data; the line is a linear least-squares fit. For the mercury ion resonance line, the required temperature is about 34°C.

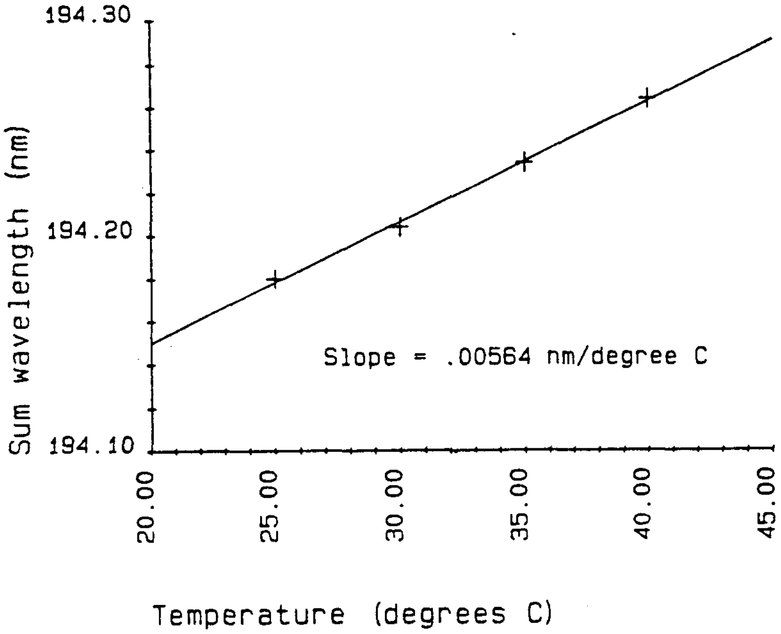

Figure 5. Temperature tuning curve for 90° phase-matched SFM in KB5.

The output power can be increased by increasing the input powers, by using the ring mixing cavity and a longer crystal, and by optimally focusing and overlapping the 257 nm and 792 nm beams. We estimate that it should then be possible to obtain several microwatts of 194 nm radiation in a bandwidth of less than 10 MHz.

If the argon ion laser were replaced by a dye laser, or other ion laser lines were used, cw radiation could be generated at shorter wavelengths, down to 185 nm or below. We note that the only other technique that has been demonstrated for the generation of coherent cw radiation below 200 nm is four-wave mixing in strontium vapor, at approximately 170 nm, by Freeman et al.[12] The lowest-wavelength cw radiation that has previously been produced by SFM in KB5 is approximately 211 nm.[13]

ACKNOWLEDGMENTS

We wish to acknowledge useful discussions with Drs. D. J.

Wineland and F. L. Walls and financial support from the Air Force Office of Scientific Research and the Office of Naval Research.

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