Infrared up-conversion with resonantly two-photon pumped metal vapors*

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We report efficient up-conversion of low-level ir radiation near 10 μ to the near ultraviolet. Radiation at 9.26 μ is converted to 3305 Å with a photon conversion efficiency of 58% and a corresponding power gain of 16.2. The process employs resonant two-photon pumping of the nonallowed 3*s*-3*d* transition in Na.

We report efficient up-conversion of ir radiation at 10.61, 10.23, 9.57, and 9.26 μ to the near ultraviolet at 3321, 3317, 3309, and 3305 Å, respectively. The process makes use of a resonantly enhanced third-order nonlinear susceptibility, which is achieved by two-photon pumping of the nonallowed 3*s*-3*d* transition of sodium.[1-4] A photon conversion efficiency of 58% and a corresponding power gain of 16.2 is obtained for the 9.26-μ conversion. These conversion efficiencies are obtained in a single coherence length of metal vapor and are therefore quite broad band in both wavelength and angular aperture.

A schematic of the resonant up-converter is shown in Fig. 1. Pumping radiation at $\omega_p = 6856$ Å, obtained from a pulsed Nd:YAG pumped $LiNbO_3$ optical parametric oscillator, and ir radiation obtained from a cw CO_2 laser are incident on a cell containing Na vapor at a pressure of about 1 Torr. The optical parametric oscillator (OPO) is tuned to resonantly excite the nonallowed 3*s*-3*d* Nd transition at 3428 Å. Although strongly excited, this transition has no dipole moment and does not radiate. Incident ir radiation at frequency ω_i couples this symmetric excitation to an allowed transition to ground, and produces radiation at $2\omega_p \pm \omega_i$. The upper side band $(2\omega_p + \omega_i)$ is much closer to the allowed 4*p*-3*s* transition, and is therefore several orders of magnitude stronger than is the lower side band.

The advantage of using a nonallowed transition to resonantly enhance the nonlinear optical susceptibility is the absence of both loss and dispersion at both the input and generated frequencies.[5] However, as a result of increased two-photon absorption, the power density of the pumping laser is restricted to a value several orders of magnitude lower than would be the case if this resonance had not been employed. The theory of this process has been examined by Harris and Bloom,[1] who show that power conversion efficiencies in excess of 100% should be obtainable in a single coherence length of metal vapor. We note that resonant nonallowed transitions have recently been used in a somewhat different manner for the generation of tunable infrared radiation.[4]

In the present experiment, the OPO had a peak output power of 3 kW, a pulse length of 20 nsec, and a linewidth of 2 cm^{-1}. It was focused into the Na cell to a confocal parameter of 2 cm, with a power density of about 10 MW/cm^2 at the beam waist. The CO_2 laser was also focused to a confocal parameter of 2 cm and was aligned colinearly with the pump beam. The cw CO_2 power entering the cell was typically about 5 mW. The CO_2 laser was tuned between various output frequencies by adding a small amount of SF_6 to the intracavity space. The intensity of radiation at the uv sum frequency was measured with a carefully calibrated Spex monochromator and photomultiplier. Measured power conversion efficiencies from infrared to ultraviolet were as follows: 10.6 μ → 3321 Å, 7.9%; 10.23 μ → 3317 Å, 10.9%; 9.57 μ → 3309 Å, 108%; and 9.26 μ → 3305 Å, 1620%. These power efficiencies correspond to photon efficiencies of 0.25%, 0.35%, 3.7%, and 58%, respectively. Once a Na pressure corresponding to a coherence length of 2 cm was reached (about 1 Torr), conversion efficiencies were quite insensitive to Na pressure. The sharply increasing conversion efficiency as the input frequency is varied from 10.61 to 9.26 μ results from the approach of the sum frequency to the 3*s*-4*p* transition frequency of Na. Conversion efficiencies are in close agreement with the theory of Ref. 1.

The realization of these high efficiencies is critically dependent on tuning the pump frequency into exact two-photon resonance. Experimentally we monitored the OPO tuning by observing the superradiant fluorescence output of a four-frequency parametric process. As the OPO was tuned to the 3*s*-3*d* two-photon transition, a strong, polarized, somewhat conical emission at 5904 Å was observed at the output of the cell. The parametric idler wave at 8173 Å was also observed. This parametric process is driven by the same resonant third-order nonlinearity responsible for the up-conversion

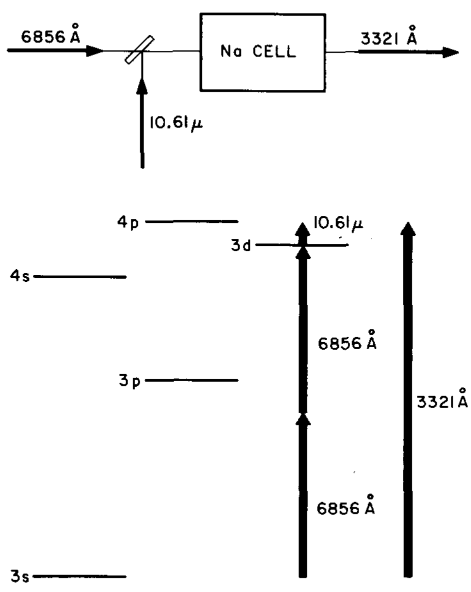

FIG. 1. Schematic of ir frequency conversion experiment.

process, and the gain at 5904 Å and 8173 Å is critically dependent on the pump detuning from resonance. Thus the visual observation of the bright yellow emission was a convenient and very sensitive indicator of proper pump tuning.

We should note that although the pumping power density in this experiment was 10 MW/cm^2, theory[1] predicts that for constant conversion efficiency, this power density may be reduced linearly with the linewidth of the pumping laser. Thus for a pump linewidth of 0.1 cm^{-1}, comparable conversion efficiencies should be obtainable at a pumping density of about 5×10^5 W/cm^2. Such densities can be reached with only 10 or 100 W of pump by increasing the Na pressure and focusing confocally to the shorter coherence length. Such a procedure should leave the conversion efficiency unchanged. In some cases it may be more convenient to excite the nonallowed transition with a combination of frequencies. For instance, Nd:YAG radiation at 1.064 μ and R6G radiation at 6119 Å may be used to excite the $3s$-$4s$ Na transition.

The device described here has a number of potentially important advantages for ir up-conversion and imaging.[6-9] These include large angular aperture, large bandwidth, and the fact that the generated frequency $(2\omega_p + \omega_i)$ is far removed from the pump frequency ω_p, and lies in a region of excellent photocathodes. A disadvantage, as compared to nonlinear crystal up-conversion, is the dependence of conversion efficiency on the square of the pump power.

This device may also be used as a generator for uv, vacuum ultraviolet (VUV), and ir radiation.[1,10] For instance, if radiation in the vicinity of 3310 Å is incident on 6856-Å two-photon pumped Na, then high quantum efficiency for generation in the 9.0–10-μ region should be obtainable. Another interesting experiment would be to use a higher-power CO_2 source (about several hundred watts) to deplete the red pump at 6856 Å. This technique should allow efficient conversion of light from flashlamp-pumped dye lasers into the uv and VUV.

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Wide-angle electro-optic switch

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A new electric-field-actuated optical switch capable of wide-angle deflection is described. The switch element makes use of the high angular selectivity of thick Bragg gratings and can be fabricated both in bulk and in thin-film configurations. Experimental verification of the switch action in a bulk configuration is presentd. Modulation of 35% was observed in this first observation of the effect.

A number of electro-optic and acousto-optic switches and deflectors have been developed in both bulk[1] and thin-film[2] forms. Many of these have rather high efficiencies, but most are characterized by having intrinsically small angular deflection ranges. In this paper, we report initial experimental results on a two-position electro-optic switch which can be fabricated both in a bulk configuration and in thin-film configurations suitable for integrated optics applications. The switch has the advantage of being able to function at any, arbitrarily large, predetermined angle. In both the bulk and thin-film forms, the switches can be cascaded into a binary array.

The wide-angle switch is based on the high efficiency and high angular selectivity of thick phase gratings. Using holographic techniques it is not difficult to construct such gratings with an angular selectivity of a few millidegrees about the Bragg angle. Forming the gratings in an electro-optic material via the "optical damage" effect makes it possible to change the average index of refraction in the grating region by the application of an