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Exploitation of an external unstable multi-pass cavity to enhance the second harmonic conversion efficiency

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ABSTRACT

Attempts to overcome the low conversion efficiency often encountered in second harmonic generation process by increasing the interaction length through usage of a number of crystals in tandem or in parallel or a single crystal in the intra-cavity or external resonant enhanced configuration have been made although with mixed success. We report here on the gainful exploitation of an unstable cavity to greatly enhance nonlinear conversion efficiency by integrating it with the stable pump cavity. This integration allowed transport of the pump radiation into the external cavity that at the same time exhibited high 'Q', prerequisite for multi-pass of the unabsorbed pump through the crystal. The unstable cavity not only ensured longer interaction length in the crystal without exposing it to high optical flux thereby safeguarding the crystal even in the pulsed operation but also eliminated the feedback problem. This scheme is demonstrated in the mid-IR region by frequency doubling of pulsed CO_2 laser emission but its advantage should persist across UV, visible, and near-IR regions too.

1. Introduction

Generation of second harmonic (SH) of the emission of a laser by establishing a phase matched condition between the fundamental and generated waves inside an appropriate nonlinear crystal has emerged as one of the most attractive methods to extend the frequency range of the available coherent sources across UV [1], visible [2], infrared [3], and mid-infrared [4] regions of the electromagnetic spectrum. As the process of conversion owes its origin to the nonlinearity of the crystal, its efficiency increases with the intensity of the pump radiation to which the crystal is exposed in a non-linear fashion. The single crystals specifically grown to provide a reasonable interaction length often suffer from low optical damage threshold. This limits the maximum pump intensity to which the crystal can be subjected to and, in turn, the overall efficiency of the SH conversion process as a result of which a significant fraction of the pump remains unutilised. The problem further multiplies in case of mid-infrared conversion as the crystals here possess intrinsically high refractive index necessitating anti-reflection coated entrance and exit faces to overcome the significant loss due to Fresnel reflection. The optical damage threshold of dielectric coatings being usually lower than the crystal bulk, the pump intensity needs to be further reduced here. Most obvious way to overcome this problem is to increase the interaction length of the pump beam with the nonlinear medium with of course due consideration to the thermal dephasing effect along the length of the crystal [5]. The cost of the crystal rises steeply with its thickness and thus usage of crystals of unconventional thickness is not economically viable. There have been attempts to use a number of crystals either in tandem [6] or in parallel [7] to increase the conversion efficiency but the inherent disadvantage in these schemes is that they present too many surfaces for the pump photons to escape through Fresnel reflections. Increased interaction length has also been obtained in the past by allowing the pump radiation to make two [8] or multiple passes [9] in the same crystal. These methods have limited application as the cavity configuration employed restricted operation in a non-collinear phase matched mode in the former case and allowed enhancing the SH conversion of only the SH wave itself in the latter case. The other schemes that have gained importance for frequency doubling of near infrared pump to the visible, albeit for cw operation, is to use the crystal in the intra-cavity mode [10] or external cavity resonant enhancement mode [11] usually in the ring configuration presumably to avoid any feed back into the pump cavity. The high intra-cavity optical flux that prevails in a pulsed laser hinders the application of these schemes for pulsed second harmonic generation (SHG). Literature on the intra-cavity or resonant enhancement external cavity for SHG in the mid-infrared region is scanty as thermal lensing leading to the possibility of crystal damage forces operation in the quasi-cw regime with adequate care taken to forbid Q-switched lasing [12] while in the pulsed operation, the intra-cavity flux has to be reduced using

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appropriate attenuators [13].

Towards increasing the effective length of interaction of the pump beam with the nonlinear medium, we have conceived the construction of a novel coupled plano-convex cavity external to the pump laser to allow to and fro passes of the unabsorbed pump through the crystal. In an ideal situation, the entrance optics of the external cavity should have high transmission at the pump wavelength to couple it efficiently inside and also sufficiently high reflectivity at the same wavelength to allow multiple passes through the crystal. This conflicting requirement is inherently satisfied by the scheme conceived by us. The scheme, in fact, has three-fold advantage. Firstly, the quality factor of the external cavity could be maintained high as the output coupler of the laser itself was made to serve as the entrance mirror of the external cavity. Secondly, transportation of the pump into this cavity was thus automatic. Finally, the unstable nature of the external cavity was instrumental in limiting the intra-cavity flux thereby safeguarding the crystal in addition to ensuring that the dynamics of the pump laser is not altered as a result of the cavity feedback. The viability of this scheme has been experimentally demonstrated in the frequency doubling of a pulsed CO_2 laser emission at ~10 μm in a commercial uncoated $AgGaSe_2$ crystal of conventional thickness. Nearly three-fold increase in the SH energy conversion efficiency and still higher increase in the peak power conversion efficiency have been achieved by making the pump, that remains unconverted in a single pass, go through the same crystal time and again. As the crystal in this arrangement offers substantial increase in the interaction length for the conversion of fundamental into SH, this scheme thus gives rise to the prospect of a thin crystal matching the performance of a thick crystal albeit at a lower level of optical flux precluding the possibility of its damage even in the pulsed operation.

In the first set of experiments (Fig. 1a) the pulsed emission of a commercial multi-atmosphere TE-CO_2 laser was made use of to effect SHG in an uncoated $AgGaSe_2$ crystal (cross-section 10 mm × 10 mm and thickness 17 mm). The 105 cm long passively stabilised pump laser cavity comprised of a plane master grating (150 lines/mm) and a concave (7 m ROC) 70%*R* ZnSe output coupler. The laser was operated on 10P(34) line giving rise to emission at 10.74 μm and consequently phase matching was found to occur for an external angle of incidence of ~34°. Usage of an intra-cavity adjustable aperture A_1 allowed the operation of the pump laser on the TEM_{00} mode. The energy incident on the crystal was controlled by adjusting the charging voltage of the laser. The usage of an adjustable aperture 'A_2' helped to restrict the cross-section of the pump beam on the crystal entrance face to ~4.5 mm diameter that allowed its clear passage through the crystal. The Fresnel reflection of the pump beam from the incident face of the crystal was utilised to monitor both energy and temporal profile of the pump pulse. The energy and temporal profile of the SH beam were also monitored after blocking the residual pump beam by a sapphire plate that also emerged with it through the crystal. By virtue of its multi-atmosphere operation, the CO_2 laser possessed intrinsically very high gain and thus delivered a pulse of relatively short duration (FWHM ~110 ns, Fig. 2) with maximum intensity, in the present experiment, being limited to ~2.5 MW/cm^2.

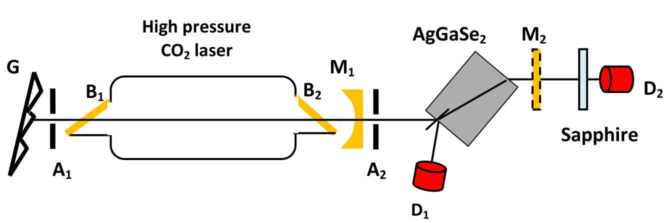

Fig. 1. Schematic diagram of the experimental setup for second harmonic conversion of the emission of a CO_2 laser in a $AgGaSe_2$ crystal. G: Plane blazed grating, A_1 and A_2: adjustable apertures, B_1 and B_2: ZnSe Brewster plates, M_1: 70% *R* ZnSe concave mirror, D_1 and D_2: energy/power detectors, M_2: dichroic mirror. (a) In case of single pass second harmonic generation, dichroic mirror M_2 is absent. (b) In case of multi-pass second harmonic generation, dichroic mirror M_2 in conjunction with pump laser output coupler M_1 forms the unstable external cavity.

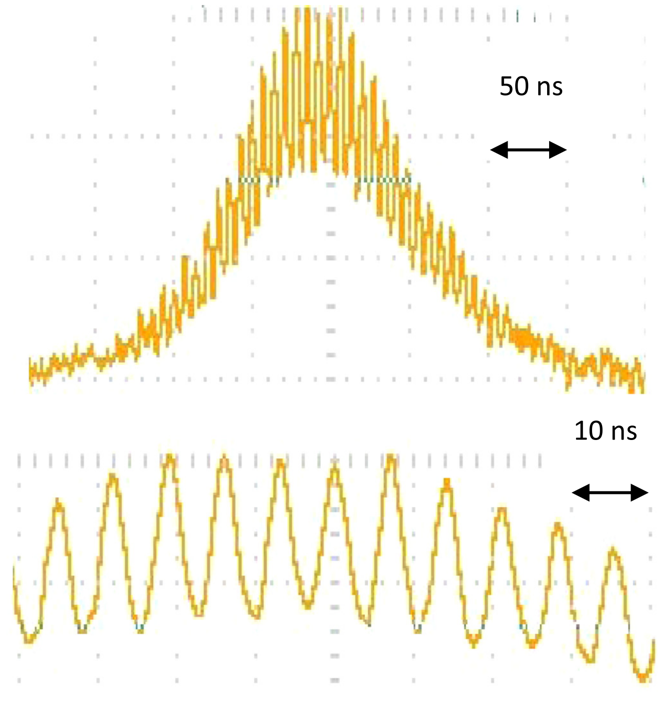

Fig. 2. Typical temporal profile of the emission of the pump CO_2 laser. FWHM value of ~110 ns is evident from the upper trace. The beating of two longitudinal modes at a period of ~7 ns is apparent from the lower trace. Absence of any beat at a longer period indicates operation on multi-longitudinal modes belonging to the same transverse family.

Towards finding the efficiency of the single pass SHG process as a function of the pump energy, we gradually increased the input and monitored the corresponding SH energy and the dependence is as shown in Fig. 3. That the SH intensity bears a square proportionality with the pump intensity is clearly evident from the parabolic nature of this curve. The maximum internal SH energy conversion efficiency can be estimated from this figure as ~8.46%. Majority of the pump energy thus stays unconverted and emerges along with the SH beam and could be measured using detector D_2 in the absence of the sapphire plate.

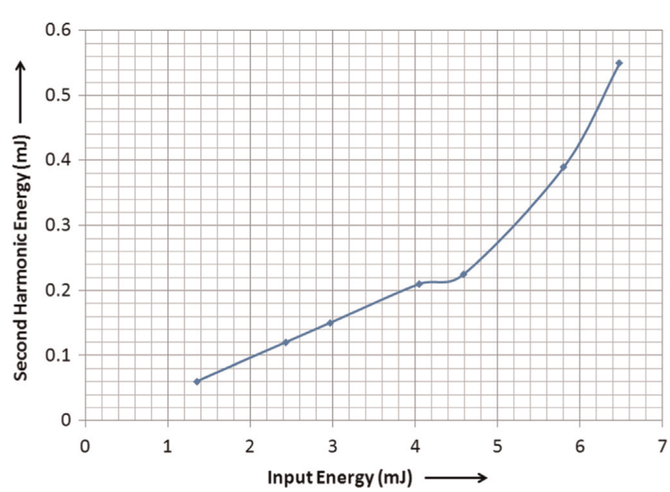

Fig. 3. Dependence of single-pass SH output on the energy of the pump pulse.