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Broadly tunable multi-output coherent source based on optical parametric oscillator

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ABSTRACT

An OPO based on KTA and ZGP crystals in tandem is demonstrated to obtain tunable coherent multi-output radiations in the 2.35–7.05 μm range and low threshold of oscillation energy pumped from a Q-switched Gaussian shaped Nd:YAG laser beam with a grating having grooves density of 85 lines/mm. The measured threshold of oscillation energy was 10 μJ. The conversion efficiency and slope efficiency of the ZGP OPO were 32.7% and 34% respectively using a 23 mm long ZGP crystal at 26 mm cavity length.

1. Introduction

High-power, coherent, multi-output light source in the 2–10 μm spectral range is of interest for many scientific and technological applications like spectroscopy, meteorology, optical counter measures, and applications based on biological and chemical detection [1–4], in lidar technology particularly two closely paced radiations for differential absorption lidar application [5,6], and generation of THz radiation and other opto-electronic device applications [7–11]. Any such application require a narrow band tunable coherent radiation source with good frequency and amplitude stability, high spectral brightness and is capable of precise wavelength resolution. Though tunable laser sources based on color center laser, ternary lead salt diode laser, quantum cascaded laser, Cr^{+2} doped ZnSe/S laser and sources based on difference frequency generation (DFG) are available in these spectral regions but sources based on optical parametric oscillator (OPO) possess some unique features and have been recognized as viable and practical coherent light sources for a wide range of applications. The potentiality of OPOs is their exceptional wavelength versatility, which allows convenient access to substantial portions of the optical spectrum with a single device by selection of suitable nonlinear material and pump source. In addition, the OPO offers a practical all-solid-state compact source, which is capable of providing high output power and efficiency, and operates at or above room temperature. These characteristics make OPOs highly competitive alternatives to conventional lasers and other technologies for the generation of widely tunable coherent radiation though the OPO process demands very high optical quality crystal; good pump beam quality and has a high pump power threshold for stable and practical operation particularly in singly resonant oscillation (SRO) mode. SRO mode is preferable to avoid mode hopping and achieve a stable output frequency and energy.

Tunable radiation in mid-infrared (MIR) and infrared (IR) spectral region had been demonstrated by number of investigators using different generation techniques like difference frequency mixing or optical parametric oscillation processes using different crystals [12–19]. But by these techniques it is possible to get only one output radiation at a time. Recently Samanta et al. [20] using two crystals demonstrated generation of two output radiation simultaneously. In this report it is demonstrated to get simultaneously three tunable radiations in the spectral range 2.35–7.05 μm, based on two OPOs in cascade using KTA and $ZnGeP_2$ (ZGP) crystals with moderate efficiency and low threshold of oscillation. The 2nd stage ZGP OPO is noncritically phase matched (NCPM) which has the advantage that, as there is no walk effect, using a longer crystal conversion efficiency can be enhanced. Again as the 2nd stage is NCPM, there is no need to re-orient this crystal to get tunable radiation. Just angle tuning the KTA crystal tunable IR radiation can be obtained.

$ZnGeP_2$ (ZGP) crystal is considered for longer wavelength generation because it is a viable candidate due to its wide optical transmission range 0.75–12 μm [21], with excellent thermal conductivity [22] (0.36 W/cm K) and high nonlinear figure-of-merit [23] (187×10^{-24} m^2/V^2) suitable for high average power application particularly for a tunable source beyond the 6 μm spectral range. With the improvement in growth technology of ZGP crystal, now-a-days there is a renewed interest of generation of tunable

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coherent source based on ZGP OPOs. ZGP OPOs either in tandem or by 2 μm from Er, Cr:YSGG laser or by Tm,Ho,$GdVO_4$ laser have been demonstrated by a number of investigators [24–40]. But all the above stated ZGP OPOs are critically phase matched suffer from walk-off effect except Vodopyanov et al. [40], which is non-critically phase-matched (NCPM).

2. Experimental

In this experiment the 1st stage OPO was a grating tunable KTA OPO pumped by Q-switched Nd:YAG laser beam operated at 1 Hz repetition rate to avoid any kind of damage on the crystal. The schematic experimental diagram is shown in Fig. 1. Using a grating instead of the 100% mirror stabilizes the frequency of operation and also reduces the line width of the generated radiation because the type-II interaction in KTA crystal has the tendency of phase matching at two different frequencies simultaneously. The grating not only stabilizes the output frequency but also reduces the line-width of the generated radiation. This is perhaps the simplest process of reducing the

line-width of the generated radiation; the line-width of the generated radiation can be reduce to a fraction of a centimeter inverse (cm^{-1}) by properly choosing the grating grooves.

For the 1st stage KTA OPO a 41° cut in the XZ plane 20 mm in length and 10×10 mm^2 cross-section KTA crystal having absorption coefficient < 0.01 cm^{-1} was used, supplied by M/S Cristal Laser of France. Both faces of the crystal have an anti-reflection coating (AR) @ 1064 nm and @ 1.3–1.7 μm. The cavity used here was a plane–plane configuration formed with a plane output mirror (M2) and a plane ruled diffraction grating (G1). The pump beam was made to be incident on the crystal by reflection from mirror (M1) (substrate BK7) placed at 45° in the cavity with following coatings: The input face of the mirror M1 has a high reflection (HR) coating @ 1064 nm at 45° and antireflection (AR) coating @ 1.3–1.7 μm while the back face was AR coated at 1.3–1.7 μm. The output mirror (M2) (substrate CaF_2) has the following coatings: the face towards the cavity was HR coated @ 1064 nm and 1.3–1.7 μm and high transmission (HT) coating @ 2–6 μm. The other surface was not coated, as Fresnel reflection loss from CaF_2 is small. The cavity was pumped by 1064 nm radiation with a pulse width of 10 ns (full width at half maximum) from a Q-switched Nd:YAG laser of M/S Lumonics. The pump beam shape was Gaussian in nature with a divergence of < 1 mrad and 3.5 mm in diameter. The grating as well as the output mirror were placed in a holder, which could be tilted in both horizontal as well as in vertical axes. In addition, the grating as well as the output mirror holder also has translation motion along the cavity axis to facilitate the change in cavity length. A micrometer screw attached with the holder was used for this purpose. The crystal was placed on a circular table capable of rotating in the horizontal plane with a least count of 0.1°. The pump beam was horizontally polarized and the polarization was rotated to vertical by a 90° polarization rotator to satisfy the o→eo interaction. The generated mid-infrared radiation (i.e. idler beam) was detected with a MCT detector operated at room temperature having detectivity $> 1 \times 10^7$ cm $Hz^{1/2}$/W (at 20 kHz) and response time ~1 ns in the spectral range 2–12 μm. We also used a quartz beam splitter (uncoated) to monitor the pump beam energy simultaneously. The cavity length was kept at 55 mm and the grating used has grooves density of 85 lines/mm, blaze wavelength of 1.35 μm. The line width of the generated idler radiation in the spectral range 2.6–3.35 μm was 2.6–4.2 nm and can be reduced further by use of higher grooves density grating and hence also the ultimate resolution in mid-infrared radiation line width. A dichroic filter was placed at 45° just after the KTA OPO to block the unconverted 1064 nm radiation (if any) to avoid any kind of damage to the ZGP crystal. The input pump beam energy as well as the generated mid-infrared energy were measured with two separate Joulemeters of M/S Gentec. The wavelength of the generated idler beam from KTA OPO was ascertained using a monochromator of M/S Spex. A part of this idler radiation (MIR say, 2.35–3.4 μm) from KTA OPO was taken out using a beam splitter (BS1) as shown in Fig. 1 just before the ZGP OPO for any other application while the transmitted part was used to pump the 2nd stage ZGP OPO. The beam splitter has 35% reflectivity @ 2.2–3.7 μm while the rest transmitted (i.e. 65%) beam energy was used to pump the ZGP OPO.

For 2nd stage ZGP OPO, a type-II cut ($\theta = 90^o$ and $\phi = 45^o$) ZGP crystal 23 mm in length and 7×7 mm^2 cross section having absorption coefficient < 0.05 cm^{-1} was used, supplied by M/S Harbin Huigong Technology Co., Harbin, China. Both faces of the crystal were anti-reflection coated at 2.2–6 μm. The cavity used here was a plane–plane configuration formed with a plane output mirror (M4) and input mirror M3. The pump beam i.e. splitted part of the output MIR radiation from KTA OPO was made to incident on ZGP crystal directly. The input face of the mirror (M3) (substrate CaF_2) has a anti-reflection (AR) coating @ 2.2–3.5 μm at normal incidence while the back face has high transmission (HT) coating at 2.2–3.5 μm and high reflection (HR) coating @ 3.7–6 μm. The output mirror (M4) (substrate CaF_2) has the following coatings: the face towards the cavity was HR coated @ 2.2–3.5 μm, partial reflection ($R \sim 90\%$) @ 3.7–7 μm. The other surface was AR coated to 10 μm. The cavity was pumped by MIR radiation 2.35–3.4 μm obtained from KTA OPO. The pump beam shape was almost similar to the 1064 nm and about 3.5 mm in diameter. The output mirror (M4) was placed in a mirror holder, which could be tilted in both horizontal as well as in vertical axes and this holder was placed on a micrometer controlled translational stage which facilitate to change the cavity length. The crystal was placed on a circular table capable of rotating in the vertical plane with a resolution of 0.1° to satisfy the o→eo interaction. As the output mirror M4 was a partial reflector @ 3.7–7 μm, the output radiation (i.e. signal and idler beam) in the range from 3.8 μm to 7 μm range was detected with a Peltier cooled MCT detector having detectivity 1.2×10^8 cm $Hz^{1/2}$/W (at 20 kHz) and response time ~4 ns in the spectral range 2–13 μm. The output radiation consists of both signal and idler radiation and using a filter having 100% reflectivity @ 3.7–5.5 μm and transmitivity in longer wavelength after the mirror M4, two radiations were separated out. One radiation lies

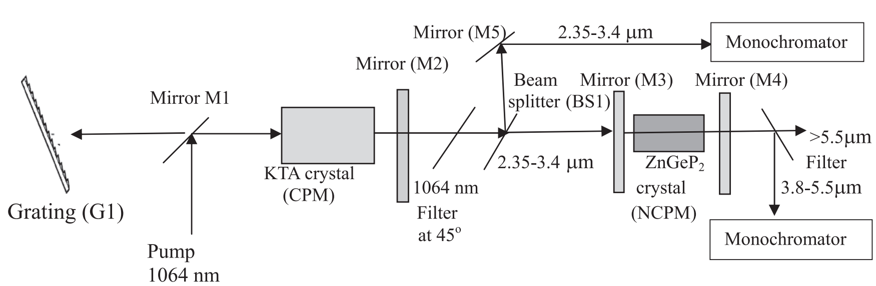

Fig. 1. : Schematic experimental arrangement for tunable multi-output source based on KTA & ZGP OPOs.