Tunable Mid-Infrared Source Based on Difference Frequency Generation of a Femtosecond Tm-fiber System in Orientation Patterned GaAs

C. R. Phillips*, C. Langrock, and M. M. Fejer
Edward L. Ginzton Laboratory, Stanford University, Stanford, California, 94305-4085, USA
*chris.phillips@stanford.edu, phone: (650) 725-2255, fax: (650) 723-2666

J. Jiang, I. Hartl, and M. E. Fermann
IMRA America, Inc., 1044 Woodridge Ave., Ann Arbor, MI, 48105-9774 USA,

A. Lin and J. S. Harris
Solid State Photonics Laboratory, Stanford University, Stanford, CA 94305

M. Snure and D. Bliss
Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433

M. Zhu
Agilent Laboratories, Agilent Technologies, 5301 Stevens Creek Blvd, Santa Clara, CA 95051

Abstract: We demonstrate a mid-infrared source tunable from 6.7-12.7 µm via difference frequency generation in orientation-patterned GaAs, with 1.3 mW average output power. The input pulses are generated from a femtosecond Tm-doped-fiber laser system.

OCIS Codes: (190.4970) Parametric oscillators and amplifiers; (190.4400) Nonlinear optics, materials; (320.7090) Ultrafast lasers; (140.3510) Lasers, Fiber; (120.3930) Metrological Instrumentation;

There is considerable interest in developing robust and compact sources in the mid-IR spectral region from 2-12 µm for frequency metrology, biological, and medical applications. A promising approach to generating light in this spectral region is by difference frequency generation (DFG) of two infrared laser sources. With DFG, established broadband laser gain media such as Er- and Tm-doped fibers can be utilized to generate light in the mid-IR. Orientation patterned gallium arsenide (OP-GaAs) is a good nonlinear material for accessing this spectral range due to its wide transparency range, high nonlinearity, and the broadband tunability enabled by quasi-phase matching (QPM) [1]. Compared to DFG employing continuous wave inputs, the use of femtosecond input pulses enables a wide-bandwidth, high conversion efficiency, and precise control of the optical frequency via the carrier envelope offset frequency. In order to avoid two-photon absorption in GaAs, a pump wavelength >1.7 µm is required [2]. Therefore, femtosecond Tm-doped-fiber lasers operating near 1.95-µm are ideally suited to mid-IR generation in OP-GaAs.

Starting from a 1.95-µm pump source, several nonlinear-optical approaches can be taken to generate the necessary IR spectral components for the DFG process. One approach is the Raman soliton self frequency shift (SFS) process [3]. SFS followed by DFG offers the potential for a broad tuning range, high conversion efficiency, and a simple single-pass experimental configuration. In this work, we use a high power 150–fs-level, 1.95-µm Tm oscillator-amplifier system to first generate a 2.5-µm seed via SFS in a fluoride fiber, followed by mid-IR generation via DFG in a fan-out OP-GaAs crystal. The mid-IR light has an average power of 1.3 mW and is tunable between 6.7 and 12.7 µm.

Fig. 1 (a): Setup of a Tm-fiber DFG system. SMF: single-mode fiber; DSF: dispersion-shifted fiber. (b) Spectrum after the LPF, measured with an FTIR.
Our experimental setup is shown in Fig. (1a). The oscillator was mode-locked by nonlinear polarization rotation and generates pulses as short as 100 fs with an average power of 20 mW at 72 MHz. The pulses were chirped in a positive dispersion fiber and subsequently amplified in a 1.6-m length of large-mode-area cladding-pumped Tm fiber [4]. We characterized the intensity and phase of the amplified pulses using SHG FROG. The reconstructed pulse duration was 145 fs (FWHM) at 1 W average power. These pulses were split into two parts with a polarizing beam splitter (PBS); we denote these parts as the pump and signal arms. The pulses from the signal arm were coupled into a single-mode fluoride fiber in order to facilitate Raman SFS from 1.95 µm to 2.5 µm. This 2.5-µm signal was then recombined with the 1.95-µm pump using a 2.4-µm long-pass filter (LPF), the corresponding spectrum is shown in Fig. (1b). The total power before and after the fluoride fiber was 200 mW and 150 mW, respectively. After the LPF, the 2.5-µm signal power was 30 mW and the 1.95-µm pump power was up to 430 mW.

Both the pump and signal beams were focused to a 30-µm 1/e² radius inside an uncoated OP-GaAs sample. The sample had a fan-out QPM grating design, with QPM period ranging linearly from 52 to 82 µm, with 22 periods; the sample length and width were 2 and 10 mm, corresponding to the x and y directions indicated in Fig. (1a), respectively. The mid-IR beam was collimated with an off-axis parabola. At optimal phasematching, the mid-IR output power was 1.3 mW. Tuning around this operating point was obtained by lateral translation of the fan-out QPM grating, which yielded a tuning range of 6.7-12.7 µm. Spectra measured with an FTIR at several different QPM periods are shown in Fig. (2a). At the edges of the tuning range, the delay and the power in the fluoride fiber were adjusted, in addition to the QPM period, in order to optimize the signal wavelength while maintaining temporal alignment with the pump. Further tuning could be obtained with an increase in pump power and shorter pump pulses. Next, we measured the output DFG power as a function of input pump power, as shown in Fig. (2b). The crystal position for this measurement was chosen to yield the largest maximum output power.

We modeled the bulk three-wave mixing process numerically, including the effects of diffraction, dispersion, \(\chi^{(2)}\) (assuming \(d_{\text{eff}}=(2/\pi) \times 94 \text{ pm/V}\)) and the nonlinear refractive index (assuming \(n_2=1.5 \times 10^{-4} \text{ cm}^2/\text{GW}\)). For Gaussian pulses with the above parameters, a maximum idler power of 2.5 mW is predicted; the corresponding B integral is approximately 0.6π. For 150-fs pulses, the group velocity walk-off length between the signal and pump pulses is 0.75 mm. Much of the reduction in observed idler power (1.3 mW) compared with theory (2.5 mW) may be due to the non-ideal quality of the pump and signal pulses. With realistic improvements to pulse energy and quality, tighter focusing, and AR-coated OP-GaAs samples, it should be possible to achieve >10 mW mid-IR power.

We have demonstrated tunable mid-IR generation through SFS of a Tm-doped-fiber laser system followed by DFG in a fan-out OP-GaAs crystal. With improvements to the pump and signal pulses, femtosecond DFG in OP-GaAs offers the potential for compact, broadly tunable, high-power mid-IR generation from 5-18 µm in a simple single-pass mixing geometry.

References