Wide tunable midinfrared difference frequency generation in orientation-patterned GaAs pumped with a femtosecond Tm-fiber system


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We demonstrate a midinfrared source tunable from 6.7 to 12.7 µm via difference frequency generation (DFG) in orientation-patterned GaAs, with 1.3 mW average output power. The input pulses are generated via Raman self-frequency shift of a femtosecond Tm-doped-fiber laser system in a fluoride fiber. We numerically model the DFG process and show good agreement between simulations and experiments. We use this numerical model to show an improved design using longer pump pulses.

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There is much interest in developing robust and compact coherent sources in the mid-IR spectral region from 2 to 12 µm for frequency metrology, biological, and medical applications [1]. A promising approach to generating light in this spectral region is by difference frequency generation (DFG) of two IR lasers. With DFG, established broadband laser gain media such as Er- and Tm-doped fibers can be utilized to generate light in the mid-IR [2,3]. 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). Compared to DFG employing cw inputs, the use of femtosecond input pulses enables a wide bandwidth, higher output power and conversion efficiency, and precise control of the optical frequency via the implementation of frequency comb lasers [4]. To avoid two-photon absorption in GaAs, a pump wavelength >1.7 µm is required [5]. Therefore, femtosecond Tm-doped-fiber lasers, which have a typical center wavelength of around 1.95 µm, are ideally suited to mid-IR operation in OP-GaAs. Furthermore, with the high peak powers available from such laser sources [6], efficient nonlinear conversion can be achieved.

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 via supercontinuum (SC) generation [7,8], although this approach yields a seed with low spectral density. A different approach is to use synchronously pumped (SP) optical parametric oscillators (OPOs) [9]. OPOs are versatile, high-power, and widely tunable, but they can be experimentally quite complex, since a free space optical cavity is usually required. The above drawbacks can be avoided by Raman soliton self-frequency-shift (SFS) sources [10], in which a substantial portion of the energy of an input pulse can be down-shifted to a spectral range of interest. SFS followed by DFG offers the potential for broad tuning, a simple single-pass experimental configuration, a limited degree of coherence, and high conversion efficiency [11].

Based on these considerations, in this work we used a Tm-doped-fiber oscillator–amplifier system to first generate 150 fs pulses at 1.95 µm. These pulses were used to 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.

Our experimental setup is shown in Fig. 1. 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-doped fiber. The pulses were then compressed in a large-mode-area fiber. We characterized the intensity and phase of the compressed pulses using second harmonic generation (SHG) frequency resolved optical gating (FROG) [12]. The reconstructed pulse duration was 145 fs (FWHM) at 1 W average power. The reconstructed pulse profile is shown in Fig. 2(a). The prepulses and postpulses are likely due to self-phase modulation (SPM) in the multimode compression fiber and can therefore be avoided with optimized fiber designs.

Fig. 1. (Color online) Setup of a Tm-fiber DFG system. SMF, single-mode fiber; DSF, dispersion-shifted fiber; PBS, polarizing beam splitter; LPF, long-pass filter.
Next, the compressed 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 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); a corresponding spectrum is shown in Fig. 2(b). We use the term “pump” to refer to the highest-frequency wave. The total power before and after the fluoride fiber was 200 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. With further optimization of the input pulse duration, SFS to longer wavelengths should be possible.

The pump and signal beams were focused to a 30 μm 1/e² radius inside an uncoated OP-GaAs sample (reflection =29% per facet). The sample length and width were two and 10 mm, corresponding to the x and y directions indicated in Fig. 1, respectively. The sample had a fan-out grating design, with a total of 22 QPM periods; the QPM period varied linearly from 52 to 82 μm over the 10 mm width. The sample was fabricated by molecular beam epitaxy (MBE) of an orientation-patterned template, followed by hydride vapor phase epitaxy (HVPE) for growth of a 1 mm thick film [13].

The output mid-IR beam was collimated with an off-axis parabolic mirror. The highest mid-IR output power was 1.3 mW. We tuned around this operating point 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. 3(a). 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. Next, we measured the average output DFG power versus the average input pump power on a thermal power meter, as shown in Fig. 3(b); the pump was attenuated between the PBS and LPF (see Fig. 1).

To compare the above results to theoretical predictions, we modeled the bulk three-wave mixing process numerically with a split-step method, including the effects of diffraction, dispersion, χ⁽³⁾ (assuming dₑₑ = (2/π) × 94 pm/V), and self- and cross-phase modulation (SPM and XPM, respectively), assuming a nonlinear refractive index of n₂ = 1.5 × 10⁻⁴ cm²/GW [14]. We assumed a temporal profile of the pump pulses corresponding to the FROG reconstruction shown in Fig. 2(a). For the signal, we assumed transform-limited Gaussian pulses with an FWHM duration of 50 fs, based on the signal bandwidth in Fig. 2(b). The beams were assumed to be radially symmetric and Gaussian, with beam waists of 30 μm (1/e²), and with focusing and temporal overlap of the pulses at the center of the crystal. The simulations, which had no adjustable parameters, are in excellent agreement with the experiment. The nonlinearity of the two curves arises through pump depletion, SPM, and XPM; these effects are relatively minor at the intensities involved here. The corresponding B-integral is approximately 0.6π at the highest pump power (430 mW), and the signal gain is approximately 1.1 dB. We note also that, based on the difference between the group velocities at 1.95 and 2.5 μm, the rate of group velocity walk-off between the pump and signal is ≈200 fs/mm.

With realistic improvements to pulse energy and quality and antireflection-coated OP-GaAs samples, it should be possible to achieve ≈10 mW mid-IR power with the average power and pulse duration currently available from the Tm-fiber system. At higher power levels, however, SPM and XPM will be important. Moderate focusing caused by these effects can lead to increases in efficiency (by increasing the intensity or overlap of the three beams). However, at higher intensities, SPM can lead to beam collapse and other unwanted effects. One way to avoid excessive SPM is to use of longer-duration (narrower-bandwidth) pump pulses. Longer pump pulses are advantageous because the plane-wave signal gain.

![Fig. 2. (Color online) (a) FROG reconstruction of the 1.95 μm pump, (b) power spectral density (PSD) of the pump and signal after the LPF, measured with an FTIR.](image)

![Fig. 3. (Color online) (a) Mid-IR output spectra measured with an FTIR at several different positions in the fan-out QPM grating, (b) average mid-IR output power for the 10.3 μm peak of (a) as a function of average pump power inside the OP-GaAs sample.](image)
scales as $I_p^{3/2}L$ for pump intensity $I_p$ and interaction length $L$, while the pump $B$-integral scales as $I_pL$. Therefore, the ratio of gain to $B$-integral scales as $I_p^{-1/2}$. In order to achieve a high gain without a large $B$-integral, this scaling favors lower intensities and hence longer pulse durations, provided that the focusing conditions and grating length are chosen optimally at a given pulse duration; at optimal crystal length and focusing, the $B$-integral scales inversely with the pulse duration. Longer pulses can be obtained from a short-pulse oscillator via spectral compression techniques [15,16].

We next consider in Fig. 4 an example to demonstrate the advantages of longer pump pulses. We assume Gaussian pump pulses with an FWHM duration of 2 ps, a $1/e^2$ beam waist of 40 μm, and energy up to 21 nJ (1.5 W at 72 MHz); we assume Gaussian signal pulses with a duration of 100 fs, a 40 μm beam radius, and energy up to 400 pJ (30 mW). Fresnel losses are neglected. A 20 mm long QPM grating is assumed, and the pulses are focused in the middle of the grating and overlapped temporally at 7 mm from the output end of the grating (this choice yields a slightly higher efficiency than the case with temporal overlap in the middle of the grating). Figure 4 shows the idler average power as a function of input average pump power for four cases (assuming a signal pulse energy of either 40 or 400 pJ, with and without SPM and XPM effects included). Since a high signal parametric gain is supported and nonlinear phase shifts are kept within tolerable levels, a high idler output power can be obtained in each case. With the same pulse energies (e.g., up to 1.75 nJ idler for the 3 mW, $\chi^{(3)}$-included curve in Fig. 4) and a 72 MHz (1 GHz) repetition rate, powers of ~10 μm (~2 mW) per comb mode are predicted.

In conclusion, 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 and have shown that with optimizations to the pump and signal pulses, DFG in OP-GaAs based on femtosecond Tm-fiber lasers offers the potential for compact, broadly tunable, high-power mid-IR generation from 5 to 18 μm in a simple single-pass mixing geometry.

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References