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Siyuan Bian, Sébastien Loranger, Raman Kashyap, Donna Strickland


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Siyuan Biana, Sébastien Lorangerb, Raman Kashyapb,c Donna Strickland*a
aDepartment of Physics and Astronomy, Guelph-Waterloo Physics Institute, University of Waterloo, 200 University Ave. W, Waterloo, ON, N2L 3G1, Canada; bThe Fabulas Laboratory, Department of Electrical Engineering, École Polytechnique de Montréal, 2900 Édouard-Montpetit, Qc, Montreal H3T 1J4, Canada; cDepartment of Engineering Physics, École Polytechnique de Montréal, 2900 Édouard-Montpetit, Qc, Montreal H3T 1J4, Canada

ABSTRACT

At Waterloo, we are developing a high power, short pulse, two-color, Yb:fiber amplifier system to generate the long wavelength (>15µm) side of the molecular fingerprint spectral region, by difference frequency mixing the two colors. This spectral region is important for trace gas detection of explosives. As an example, it has been shown that the strong spectroscopic signatures of a peroxide-based explosive triacetone triperoxide (TATP) occur between 15 and 20 µm. To date, we have achieved a tuning range from 16 to 20 µm with a maximum average power of 1.7 mW. On the short wavelength side, the two colors would need to be pulled further apart, which requires a higher power seed to beat the amplified spontaneous emission that appears at the gain peak of the amplifiers between the two seed colors. On the long wavelength side, we are limited to 20 µm by the transparency region of the nonlinear crystals. We would like to find new nonlinear materials that have transparency from 1 to 30µm. If we could generate wavelengths from 15 to 30 µm with sufficient power, we could extend the spectral region to also cover 8 to 15µm by frequency doubling the longer wavelengths. We are currently working on replacing bulk optics in the system with fiber based optical elements to select the wavelengths as well as stretch and recompress the pulses in order to make the system compact and stable.

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Keywords: Fiber Lasers, Mid-infrared, Fiber Bragg gratings

1. INTRODUCTION

Small coherent sources of radiation in the spectral region of 5 to 20 µm would open up the field of infrared spectroscopy in the fingerprint region, where a number of functional groups have strong absorption signatures.[1] In recent years, much work has gone into developing efficient sources of mid-infrared radiation with wavelengths between 3 and 5 µm for molecular spectroscopy where many organic compounds of environmental importance have strong absorption signatures.[1] However, many functional groups have strong absorption signatures at long wavelengths. As an example, THz spectroscopy was used to measure spectroscopic signatures of peroxide-based explosives at wavelengths longer than 50µm.[2] However their numerical simulations of the explosive triacetone triperoxide (TATP) showed that the strongest absorption is between 15 and 20 µm, where the authors were unable to measure the spectra.

No laser source can tune over the entire fingerprint spectral region. A free-electron laser has been used to generate infrared wavelengths tunable from 6 to 30 µm in order to investigate amino acid conformations.[3] The most common coherent sources of radiation in the fingerprint region are Quantum Cascade Lasers (QCL).[4] Although traditional laser spectroscopy uses narrowband lasers, a new field of high resolution spectroscopy has been emerging over the last few years, namely frequency comb spectroscopy.[5] Very recently frequency combs have been generated in QCL’s,[6] however, frequency combs more commonly result from mode-locked lasers. Very few mode-locked QCL’s have been demonstrated and the bandwidths are relatively narrow.[4] On the other hand, broadband mid-infrared (MIR) can be generated by difference frequency mixing two ultrashort pulses. If the two pulses originate from the same mode-locked laser, then the MIR radiation has the carrier envelope offset eliminated making a perfect frequency comb.[7]
We are developing a two-color, short pulse Yb:fiber laser system to generate long wavelength mid-infrared radiation through difference frequency mixing. MIR has been generated by difference frequency mixing the output of a two-color, mode-locked Ti:sapphire oscillator. [8] However, the nonlinear mixing efficiency was low generating just ~5µW of average power at a wavelength of ~10µm because of the low average power of the Ti:sapphire laser. We previously developed an amplified two-color Ti:sapphire laser system, that offers high intensity pulses at a low repetition rate of 10 Hz. [9] The very broad gain bandwidth of Ti:sapphire allowed the two peak wavelengths to be over 100 nm apart and so could be used to generate several µJ pulses of MIR radiation from 9 to 11 µm. Amplified,mode-locked Yb:fiber laser systems are smaller and more efficient having the advantage of producing significantly higher average powers than Ti:sapphire amplifiers, with over 100 W of average power from a Yb:fiber CPA system being reported.[10] Recently short pulse fiber laser systems have been used to generate long wavelength MIR through difference frequency mixing, but, the average power is still low. [11,12,13,14, 15,16] The MIR is produced by difference frequency mixing a pump pulse from a fiber laser and a tunable second pump pulse, created by focusing some of the fiber laser output into either a photonic crystal fiber (PCF) to make a continuum[11,12] or a strong Stokes pulse[15] or an anomalous dispersion fiber to make a Raman shifted soliton pulse,[13,14] or two PCF’s to have both a strong Stokes and a continuum.[16] Typically the maximum power is at a shorter wavelength of ~ 6 µm and the power decreases with increasing wavelength because the nonlinear mixing gives a constant photon conversion efficiency. The highest average power above 10µm using a fiber laser pump is 0.6 mw with the spectrum peaked at 12µm.[14] The highest powers for long wavelength MIR to date come from a dual-signal-wavelength optical parametric oscillator (OPO) pumped by a solid state laser. [17] 1.45 W of power from the OPO generated 4 mW at 13 µm by difference frequency mixing in a 3 mm AgGaSe2 crystal. To achieve the longer MIR wavelengths, they used a 1 mm GaSe crystal and achieved average power of 0.8mW at the longest wavelength of 16µm.

Rather than using some of the fiber laser pump power to generate a continuum and mix the remaining pump with a segment of the continuum, it is more efficient to amplify two colours within the laser gain medium and frequency mix the total output of the amplifier. By using a single amplifier chain to amplify the two colours, the timing jitter between pulses is reduced resulting in a higher nonlinear mixing efficiency. We have previously reported generating MIR over the range of 16 to 20 µm at power of 1.5 mW using a Yb:fiber CPA system, with a relatively modest laser power level of 2.5 W.[18] Unlike the other tunable MIR sources, the power does not decrease with increasing wavelength because the power of the pump pulses increases as the two colors are brought together and closer to the gain peak of the Yb:fiber amplifier. In this paper we discuss laser developments to increase the color separation and simplify the system by replacing some bulk optic components with fiber laser components.

2. EXPERIMENTAL CONFIGURATIONS

Three-stage Yb:fiber amplifier

The front end of the fiber system is the same as in the previously reported two-stage amplification system.[18] The two colors in the Ti:sapphire system were generated in a two-color, mode-locked Ti:sapphire oscillator [19]. Although a two-color mode-locked Nd:fiber oscillator has been demonstrated[20], it could not achieve the synchronous mode-locking of the two colors as occurred in the Ti:sapphire system. For this reason, we use continuum generation in a photonic crystal fiber to create a broad spectrum from which the two colors can be selected. The continuum is generated by focusing 160 mW average power from a 200 fs, 1030 nm, Yb fiber laser, into a 2 m photonic crystal fiber, with a dispersion null at 1040nm. By rotating a half-wave plate placed before the photonic crystal fiber, the continuum spectrum can be altered. The photonic crystal fiber is spliced to 100m of single mode fiber to stretch the pulse duration. The other end of the single mode fiber is spliced to a Faraday isolator. At the output of the isolator, the continuum has a total power of 27mW with a 200 nm bandwidth. To select the two colors a three grating pulse stretcher is used. Knife edges are used in the focal planes of the stretcher to eliminate the central wavelengths between 1040 and 1100 nm. At the output of the grating stretcher, the power is 2 and 0.5 mW in the short wavelength and long wavelength colors, respectively.

In the previous work, we used a two-stage amplifier to bring the total power to 2.5 W before the compression stage. The pre-amplifier is a highly-doped, single-mode, single-clad YDFA. The pre-amplifier fiber length was 7.5 m and it is co-pumped by 350 mW and counter-pumped by 500 mW from 986-nm, single-mode, fiber-coupled diode lasers. At the highest pump powers, there was ASE present between the two colors. Two notch filters were used to eliminate up to 55nm of bandwidth between the two colors. A Faraday isolator was also placed between the first and second amplification stages. The second amplifier was comprised of a 10.5 m length of polarization maintaining, single mode...
double-clad Yb:fiber, counter-pumped up to 6 W from a 975-nm, multi-mode, fiber-coupled diode laser. With this two-stage arrangement we were able to pull the peak wavelengths 71 nm apart before the ASE in between the colors saturated the gain. After a three-grating compressor, the maximum obtained power was 1100 and 100 mW for colors peaked at wavelengths 1043 and 1105 nm respectively. With these powers we achieved 1.5 mW of average power at a MIR wavelength of 18.5 µm by difference frequency mixing the two-color output in a 1mm thick GaSe crystal.

To further separate the colors, higher seed power must be input to the final amplifier. We are now using three stages to generate this higher power, more widely spaced two color spectrum. The new three stage system uses a 7m, single-mode, single clad, low-doped Yb:fiber counter pumped by a single mode fiber coupled 975nm diode laser for the pre-amplifier. There is a Faraday isolator between the pre-amplifier and the second amplification stage, comprised of 8m of single mode, double clad, non-polarization preserving fiber, pumped by a 5 W multimode fiber coupled diode laser. After this amplification stage, the two-color beam passes through a single notch filter to eliminate a 45nm bandwidth of ASE and then passes through a Faraday isolator. The final amplification stage is the same as used in the two-stage system.

**Two-color pre-amplifier with chirped fiber Bragg gratings**

Towards making the system more compact and all fiber, we replaced the grating stretcher and color selector with two chirped fiber Bragg gratings (CFBG) spliced on one end of the pre-amplifier fiber. For this initial study with Bragg gratings, we chose to have the center wavelengths 70 nm apart to compare with our largest separation obtained with the bulk gratings. The center wavelengths of the CFBGs were at 1035 and 1105 nm. The 2 CFBGs, developed at Polytechnique Montreal, are unapodized chirped gratings of 5 and 10 mm in length, respectively both with a bandwidth of 5 nm, giving a delay of 10 and 20 ps/nm respectively. Gratings were fabricated using the direct writing holographic method with a Talbot interferometer and a 213 nm wavelength 5th harmonic of a solid-state Nd:YAG laser[21]. In this system, a hydrogen loaded fiber moves using an ultra-precise translation stage while the phase mask position is modulated by a saw-tooth wave using a piezo element to synchronize the position of the fringe pattern with the movement of the fiber. Chirp was induced by sweeping the frequency of the saw-tooth wave, thus changing the fringe pattern period. However, limitations in the sweep range of the saw-tooth restricts the bandwidth of the chirp in the grating to ~5 nm.

The new amplifier arrangement is depicted in Figure 1. Because we are using chirped Bragg gratings we removed the 100m single mode fiber and Faraday isolator. We found that we still had to eliminate the seed wavelengths at the gain peak of the pre-amplifier, in order to maximize the power in the two output colors. The continuum seed beam from the photonic crystal fiber passes through a notch filter to eliminate wavelengths between 1040 and 1090 nm. The beam then travels through a Faraday isolator and is focused into the 7.5m, low-doped, single-mode, and single-clad Yb:fiber pre-amplifier at the opposite end from the Bragg gratings. The 975 nm pump is focused into the same end through a dichroic mirror. Two spectral bands were directed back through the pre-amplifier by the CFBG’s. The amplified two colors return through the Faraday isolator and reflect off the second polarizer. This beam is then sent to the final two fiber amplifiers. Since the pre-amplifier is not polarization preserving, we use a half-wave plate between the Faraday isolator and pre-amplifier to optimize the output power. The two colors experience different polarization rotation in the pre-amplifier. By rotating the half-wave plate we can vary the power ratio of the two colors.
Figure 1. Schematic of seeding the continuum spectrum into the pre-amplifier with chirped fiber Bragg gratings.

3. RESULTS AND DISCUSSION

Three-stage Yb: Fiber amplifier

The goal of the three-stage system was to increase the tuning range of the two colors. With the three-stage system, the maximum power before the compressor was 2.6W, similar to the two-stage system because the final stage was the same. However, the highest power achieved after the compressor was 1700mW and 80 mW for colors peaked at wavelengths 1038 and 1103 nm respectively. The amplified spectrum is shown in Figure 2. The fact that more power was available after the compressor indicates that most of the amplified power is in the two colors with very little in the ASE, which is eliminated in the compressor. A small amount of ASE is evident in the spectrum from 1085 to 1100 nm. This is because only a single notch filter was used. This ASE is a result of amplification in all three stages. No ASE from the final stage is measured between 1045 and 1085nm, which contrasts the results from the two stage system.[18] This is because we seeded the final stage with over 100 mW of power. This power is still relatively low because we were using non-polarization preserving fiber for both of the first two stages and both colors exhibited different amounts of polarization rotation in each fiber. A wave plate was used before each Faraday isolator to vary the ratio of power between the two colors, but the colors could not both be optimally transmitted through the polarizers. The pre-amplifier, pumped at a power of 150mW, generated 22mW of power with 10 mW after the Faraday isolator. There was no measurable ASE and so no notch filter was used at this stage. After the second amplifier, power up to 800 mW can be generated, but the notch filter not only eliminates the ASE, but reduces the power in the two colors by 50% and then the optimum power through the Faraday isolator was just 120mW. With the amplified spectrum shown in Fig. 2, 1.7mW of power was achieved for a MIR wavelength which peaked at 17.6μm. This MIR power was measured with the HgCdTe detector as previously, but was also confirmed with a thermal detector assuming 67% absorption in the Ge filter. The lack of ASE shows that the two colors could still be further separated, but the MIR power was reduced when the color separation was increased.
Two-color pre-amplifier with chirped fiber Bragg gratings

Figure 3 shows the output spectrum from the pre-amplifier with the CFBG, pumped at a power of 250 mW. The total output power from the Faraday isolator was 22 mW. The wave plate was rotated to maximize the power of the long wavelength. At higher pump power, only the short wavelength power was increased and did not have an effect in the output of the next amplifier. We should have used a longer fiber for these wavelengths or used a shorter wavelength Bragg grating for the short wavelength color. There was no ASE between the two colors that needed to be removed before sending the amplified seed to the next amplification stage.

This spectrum was then sent to the identical two final stages of the three-stage system. The output power after the gratings was 700 and 210 mW for the short and long wavelength colors, respectively. The wave plates were rotated to maximize the long wavelength power. When the wave plates were rotated to maximize the total power, the colors had 1010 and 30 mW in short and long wavelength colors, respectively. The ASE was reduced in comparison to the bulk grating case. The two colors have narrower spectra as dictated by the width of the CFBG. We were not able to properly compress the pulses because the long chirp of the Bragg gratings could not be fully compensated with the small gratings of our compressor, so no attempt at MIR generation was made with this system.
Figure 4. Two-color spectrum at the output of final fiber amplifier using the CFBG pre-amp, before the compressor.

4. CONCLUSIONS AND FUTURE DIRECTIONS

The three-stage amplifier shows that for sufficiently high power seeding the two colors can still be pulled further apart before ASE dominates the gain. The amplifier design is still far from optimized. In the near future, we will use a polarization maintaining fiber for the second stage, which will allow more of the radiation to pass through the Faraday isolator and provide a much stronger seed power to the final stage. This stage will then use a large mode area fiber to have higher output powers for better power conversion to the MIR wavelengths. In the future, our plan is to use a very broadband fiber Bragg grating to eliminate the wavelengths between 1040 and 1100 nm and so more resemble the bulk color selector. The bandwidths of the amplified colors will then not be limited by the widths of the CFBG’s. Also the stretching can be simply done with the 100m single mode fiber, which can then be easily compensated by the grating compressor. We would like to be able to have these wide bandwidth fiber Bragg gratings for both the single clad pre-amplifiers as well as the double clad fiber amplifiers to clean up the ASE at each stage allowing even wider color separation and more tunable MIR spectral range covering the long wavelength side of the fingerprint region.

REFERENCES