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Executive Summary of the Thesis

Ultrafast Yb:CALGO amplified laser for broadband mid-infrared generation

Laurea Magistrale in Physics Engineering - Ingegneria Fisica

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1. Introduction

The term "broadband mid-infrared light" refers to a region of the electromagnetic spectrum spanning 2-20 µm (500-5000 cm^{-1}) crucial for a large number of applications. The practical interest of this interval comes from the presence of the fundamental vibrational modes of most of the molecules [1] that makes mid-infrared a versatile tool for spectroscopy in the molecular fingerprint (500-1800 cm^{-1})[2].
In the last two decades, the large number of perspectives in terms of applications produces an intense research activity on mid-infrared sources. Despite the great effort, covering this spectral region with conventional laser technologies remains a challenge. Among the sources that demonstrate to emit in this spectral range, those based on intrapulse difference frequency generation (IDFG) represent the most attractive since allows to employ near-infrared mode-locked femtosecond lasers which are a well-established and exploited in many fields. The strength of these systems is the versatility that allows also other applications such as the generation of terahertz radiation [3] and of 4^{th}-harmonic [4] by simply change the crystal.
In this thesis work, we proposed the design and the characterization of a setup that produces amplified few-optical-cycles pulses for broadband mid-infrared generation starting from a mode-locked Yb:CALGO laser emitting at 1 µm. The initial pulses are characterized by a duration of 70 fs and an average power of 45 mW. By combining amplification in Yb-doped fiber amplifier and optical compression, we produces pulses with a duration of 80 fs and an average power of 5 W. These are then coupled into a photonic crystal fiber (PCF) where supercontinuum generation happens producing 100 nm spectral broadening. If the obtained pulses are optically compressed and focused into an orientation-patterned gallium phosphide (OP-GaP), we can produce by exploiting IDFG a radiation spanning the mid-infrared range.

2. Experimental setup

The experimental setup used to generate amplified pulses is shown in Figure 1. In the first part, the $sech^2$-pulses emitted by a mode-locked Yb:CALGO are coupled by a pair of gold mirrors into an Ytterbium-base fiber amplifier. The latter is constituted by a pump diode emitting at 976 nm in correspondence of the absorption peak of the Ytterbium, by a wavelength division multiplexing (WDM) which combines signal and pump, and by 3-meter long Yb-doped polarization-maintaining active fiber. At the output, the residual pump is separated from the amplified signal by means of a dichroic mirror. The chromatic dispersion accumulated in fiber is compensated by an optical compressor made by a pair of diffraction gratings in double-pass configuration. The pulses coming from the amplifier are driven within the compression stage by means of an Yb-fs mirror that ensures minimum effect on the pulse dispersion. The same holds for the low-GDD mirror used as roof mirror in the optical compressor.

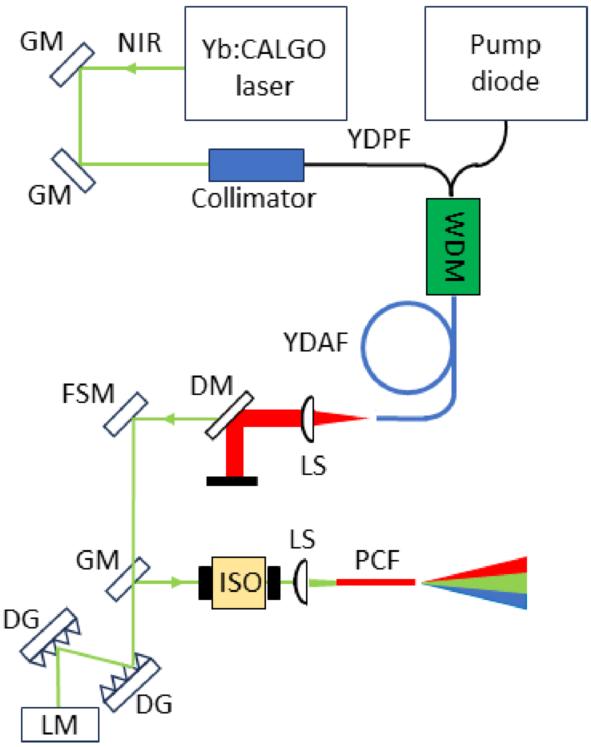

Figure 1: Experimental setup. DG: diffraction gratings; DM: dichroic mirror; FSM: Yb-fs mirror; GM: gold mirror; ISO: optical isolator; LM: low-GDD mirror; LS: lens; PCF: photonic crystal fiber; YDPF: Yb-doped active fiber; YDPF: Yb-doped passive fiber.

The resulting pulses characterized by a duration of 80 fs and an average power of 5W pass through an optical isolator avoiding the back reflections that could damage the components of the system. Then, these are coupled by means of an aspheric lens into 15-cm long photonic crystal fiber (PCF) where the supercontinuum generation happens. The chromatic dispersion accumulated in PCF can be subsequently compensated by means of a pair of prisms in double-pass configuration or in alternative by 15.4-cm long hollow core fiber. The resulting few-optical-cycles pulses can be focused in an orientation-patterned gallium phosphide crystal producing a radiation spanning the mid-infrared range.

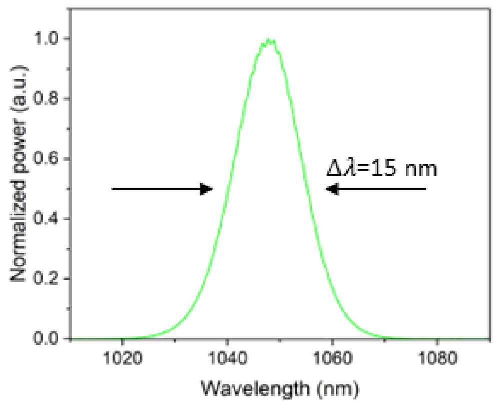

Figure 2: Normalized optical spectrum of Yb:CALGO laser for a pump current of 0.65 A.

3. Experimental results

3.1. Yb:CALGO characterization

We started characterizing the pulses emitted by the Yb:CALGO. During all the measurements, also in the ones displayed in following subsections, the repetition rate of the laser remained fixed at 160 MHz while the pump current at 0.65 A. Further, the optical spectra were taken with a resolution of 1 nm while the intensity autocorrelations with a resolution of 10 fs.

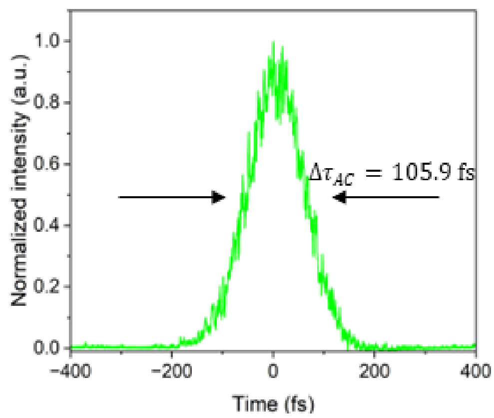

Figure 3: Normalized intensity autocorrelation of Yb:CALGO laser for a pump current of 0.65 A.

The optical spectrum measured at the output

of the laser is shown in Figure 2. As we can see, it is centred around 1050 nm and it is characterized by a full width at half maximum (FWHM) of about 15 nm.
The pulse duration was retrieved from the FWHM of the intensity autocorrelation measured by means of a commercial non-collinear second-harmonic generation autocorrelator. The measurement is shown in Figure 3. Here, we notice a full width at half maximum of 105.9 fs that, if divided by a factor 1.54 characteristic of the $sech^2$-pulses, produces 69 fs.

3.2. Pulse characterization after amplification and optical compression

At the output of the Yb-doped fiber amplifier, we performed some power measurements. Figure 4 shows the values of average power as function of the pump current. The maximum value reached is about 5 W. Except for technical limitations, the result could have been even higher since the maximum pump power achievable by the diode is 70 W and here only 15 W were used. However, the intended purpose of this thesis work was 5 W and so we stopped there avoiding also some instabilities and damages that could rise at such high powers.

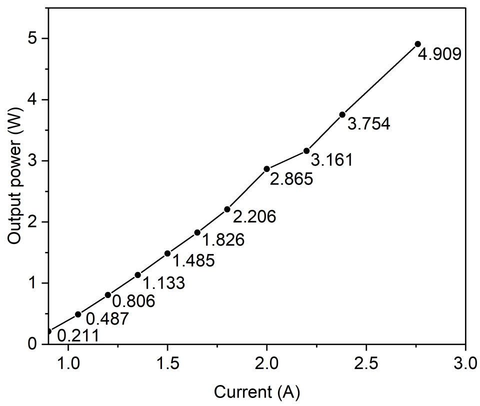

Figure 4: Average power as function of the pump current at the output of fiber amplifier.

Figure 5 shows the relative intensity noise (RIN) measurements performed after the amplifier. As expected, at low frequencies the extra electronic noise introduced by the fiber amplifier causes a degradation of the RIN of the amplified signals with respect to the one of Yb:CALGO. At higher frequencies, the filtering effect of the Ytterbium upper level is indicated by the reduction of the RINs of the amplified signal with respect to the one of the pump alone. For frequencies higher than 10^6 Hz all the traces, apart from the one of the pump, reach the noise floor the level of -130 db/Hz.

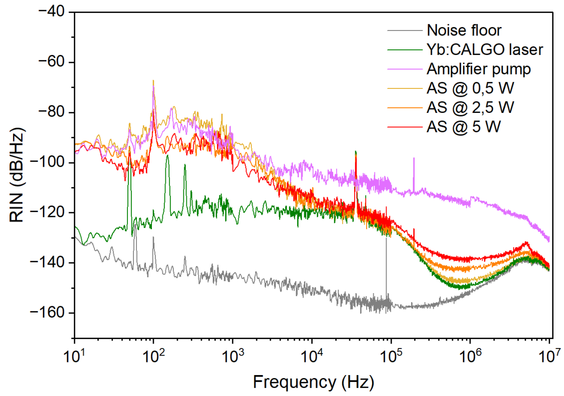

Figure 5: Relative intensity noise of Yb:CALGO and amplified signals (AS).

The amplified pulses are then optically compressed by means of a pair of diffraction gratings. The output average powers are slightly lower with respect to the one shown in Figure 6 due to the 20% losses introduced by this stage. However, since our goal was to reach 5 W, we increased a little bit the pump current of the amplifier obtaining that value.

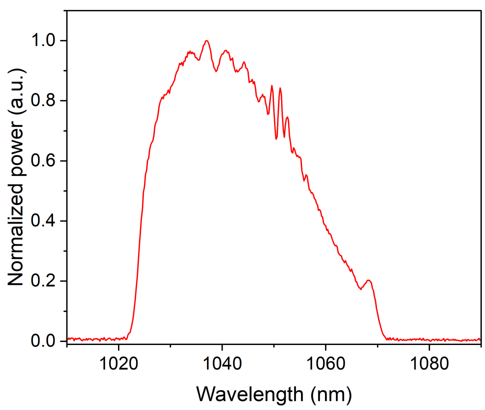

Figure 6: Normalized optical spectrum after the fiber amplifier and the compression stage for an average power of 5W.

The optical spectrum measured after the compression stage for a power of 5W is shown in Figure 6. The broadening characterizing it could be an effect of the propagation in the Yb-doped

active fiber also confirmed by the shift torward lower frequencies that seem to be caused by the intrapulse Raman scattering. Further, on the right of the optical spectrum we see some peaks which indicates the presence of a lasing effect.
Figure 7 shows the intensity autocorrelation after the compression stage for an average power of 5 W. The corresponding pulse duration for a FWHM of 130 fs is about 84 fs underlying an efficient compensation of the chromatic dispersion accumulated in the fiber amplifier.

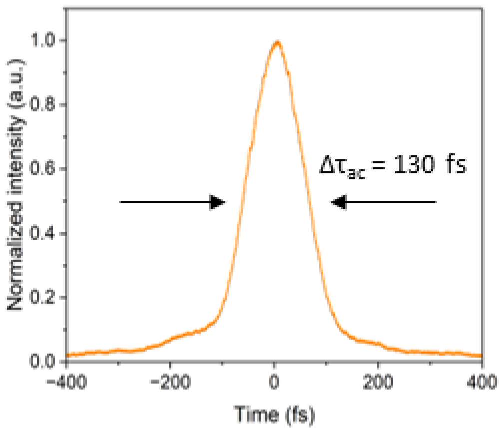

Figure 7: Normalized intensity autocorrelation after the fiber amplifier and the compression stage for an average power of 5 W.

3.3. Supercontinuum and mid-infrared generation

The amplified and optically compressed pulses are focused into a photonic crystal fiber where the spectral broadening shows in Figure 8 is obtained. As indicated in figure, these spectra were measured for an output PCF average power of 1 W. Indeed, the optical isolator placed before the fiber causes a 20% reduction of the average power. Further, the power coupled in PCF is about 60%. To be precise, 1 W is less than half of the power achievable that is 2.5 W. Already with this value, we were able to obtain a spectral broadening of about 50 nm. We expect that with the maximum power, it would be at least equal to 100 nm.
After the PCF, there would be another compression stage. However, the impossibility of implementing a high-resolved characterization technique required by pulses with a duration lower than 20 fs, does not allow us to finely tune the distance among the prisms and to collect experimental data. As consequence, we limit to some estimations about the pulse duration assuming to achieve transform-limited pulses. Considering a brodening of 100 nm, the compression factor F defined as the ratio between FWHM of the broadened and of the initial spectrum is equal to 6.67. This means that the resulting fully-compressed pulses would have approximately a duration of about 12 fs.
In terms of relative intensity noise, we expect a degradation at low frequency caused by the modulation instabilities that govern high-order processes characterizing the supercontinuum generation. Also at high frequency, there might be a degradation of white noise floor due to nonlinear amplification of the input pulse shot noise.

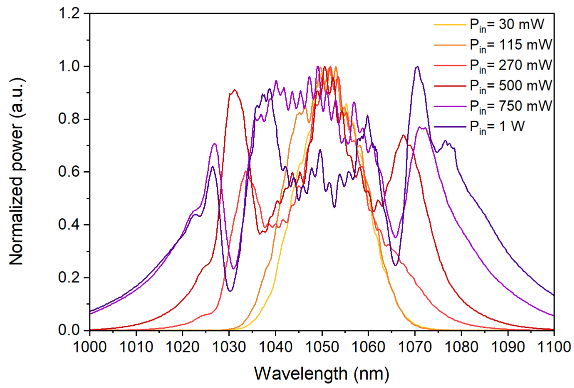

Figure 8: Spectral broadening for power going from 30 mW to 1 W.

The reason mentioned above and the difficulty in finding the crystal do not allow us to produce a broadband mid-infrared radiation. As consequence, the values provided come from an estimation. In particular, this was done by considering the work reported by Nakamura in Ref. [2] since the characteristics of the pulses achieved are similar. The crystal choosen is an orientation-patterned gallium phosphide with a thickness of 0.8 mm. Nakamura produced twice our spectral broadening obtaining a spectrum spanning 8.1-13.1 μm (760-1240 cm^{-1}) for a grating period of of 27 μm and 9.8-17 μm (590-1020 cm^{-1}) for a grating period of of 31 μm. We roughly estimate to obtain for the same periods, respectively, 9.5-12 μm (830-1050 cm^{-1}) and 11.6-15 μm (666-860 cm^{-1}). In terms of average power, we expect few milliwatt.

4. Conclusions and future developments

In this thesis work, we demonstrated a simple approach for the generation of amplified few-optical cycles pulses starting from the a mode-locked Yb:CALGO laser emitting at 1 µm. The pulses obtained are characterized by a duration of 80 fs and an average power of 5 W. By combining supercontinuum generation in PCF and optical compression, we estimate to achieve pulses with duration of 12 fs and an average power higher than 2.5 W that if focused in OP-GaP crystal they can produce by exploiting IDFG a radiation spanning the mid-infrared range.
The results are in line with previous experiment like the one proposed by Nakamura [2] and for this reason they can be considered satisfactory. On the other hand, we know the potential of our system and we are confident that future versions could achieve better results especially in terms of efficiency and of output average power.

5. Acknowledgements

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References

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