Relazione sull'attività di ricerca del Dr. Pietro Malara nell'ambito del Programma "CNR Short-term Mobility" 2009, avente per oggetto: "Development and applications of innovative quantum cascade lasers", svolta presso la school of engineering and applied sciences, Harvard University, Cambridge MA (U.S.).

Mode-locked lasers are key elements for many important applications such as nonlinear frequency conversion, time-resolved measurements and frequency combs. To date, the most common approach to generate short pulses in the mid-infrared relies on the down-conversion of short wavelength mode-locked lasers through nonlinear processes such as optical parametric generation or difference frequency generation. These systems are usually bulky, expensive and typically require a complicated optical arrangement.

Quantum cascade lasers (QCLs), since their invention in 1994, have become the most prominent coherent light sources in the mid-infrared. One of their most striking features is that emission wavelength, gain spectrum, carrier transport characteristics and optical dispersion can be completely engineered. This makes QCLs a unique candidate to serve as a semiconductor source of ultra-short pulses in the mid-infrared.

However, an obstacle of fundamental origin has so far prevented achieving stable ultrashort pulse generation in QCLs. In intersubband transitions, the carrier relaxation is extremely fast because of optical phonon scattering. As a result, the gain recovery time in QCLs, determined mainly by the upper state lifetime, is typically on the order of a few picoseconds: one order of magnitude smaller than the cavity roundtrip time of 40-60 ps for a typical 2-3mm-long laser cavity.

According to conventional mode-locking theory, this situation prevents the occurrence of stable passive mode-locking and impedes the formation of high-intensity pulses through active mode-locking. In fact, if the gain recovery is much shorter than the cavity roundtrip time, multiple pulses can propagate in the laser cavity, separated, approximately, by the gain recovery time.

The scientific subject of my period in the Capasso group at Harvard university consisted in the development and the preliminary study of a new strategy to overcome this problem. The proposed experimental scheme is shown in fig. 1

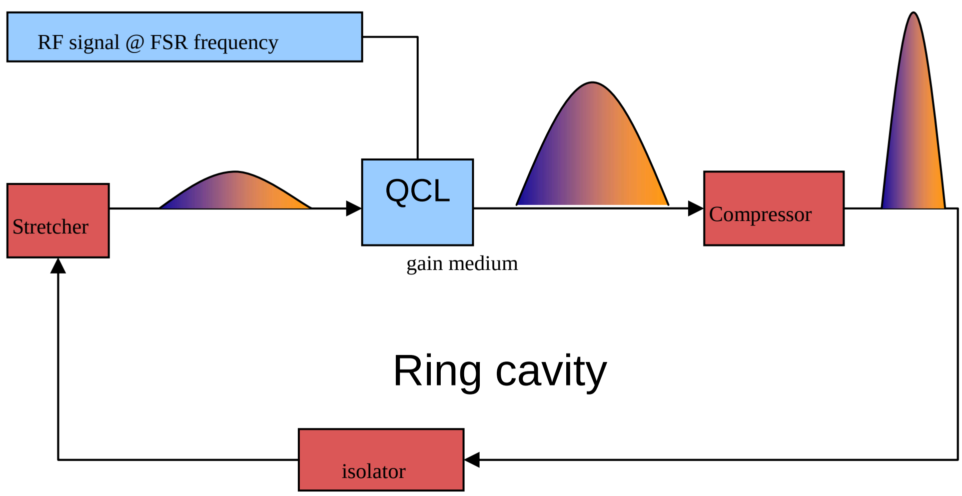

Fig 1-Experimental scheme for the mode locking of a QCL around 8 microns

The basic principle consists in including a QCL gain medium in an external ring cavity equipped with a positive and a negative dispersion compensation elements (pulse stretcher and compressor). The apparatus recalls the well known principle of chirped-pulse amplification, except that the pulse width management is performed intracavity. The behaviour of such a laser, when driven in mode-locking regime, is commonly referred as to" breathing-mode". In fact, a modelocked pulse is compressed at any round trip before being extracted from the cavity, and stretched before injecting the gain medium. If the stretching/compressing ratio is sufficiently high, the pulse that transits in the QCL medium is so broad to be almost indistinguishable from a CW beam. In this way, the problems relative to the fast QCL gain recovery time could be in principle overcome. The broad amplified pulse is then recompressed and a fraction of its energy coupled out of the cavity.

Dispersion Management.

The starting point is establishing the amount of dispersion one has to achieve. In order to simulate a quasi–CW radiation, the pulse spatial FWHM must be comparable with the gain medium length. Considering that the latter is around 3mm, it follows that a pulse of at least 30ps is needed prior to the amplifying stage. Supposing that pulses as broad as 3 ps can be provided by gain modulation [], an amount of group velocity dispersion as large as 20 ps^2 has to be introduced and subsequently compensated.

With this in mind, a number of possibilities for the strectching/compression elements have been analyzed, from prism arrays commonly used in Ti-Sa lasers, to fiber chirped-bragg-gratings. A good compromise between the amount of introduced GDD and its tunability can be provided by a double-pass grating-based Martinez-type strectcher and compressor, whose schemes are illustrated in fig. 2.

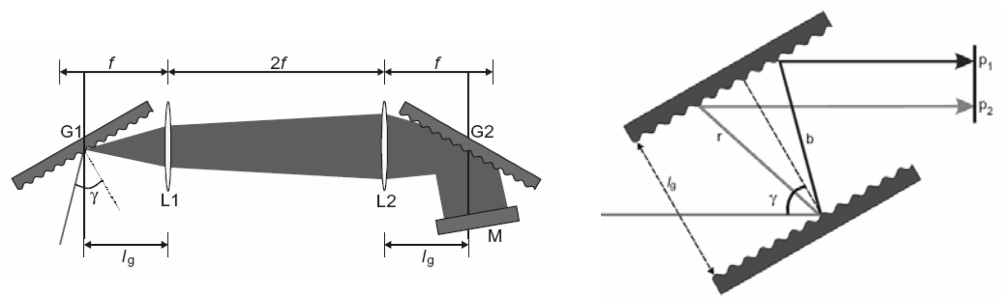

Fig 2 – Martinez type stretcher (a) and compressor (b)

As shown in fig. 3, a simulation of the behaviour of such elements in a cavity showed that a pulse of a few picoseconds can be stretched by an order of magnitude by using the following parameters: lenses of 50mm, gratings 200 lines/mm, distance between grating and lens Lg=30mm. A compressor like in fig.2b with distance 28cm can easily compensate such a GDD.

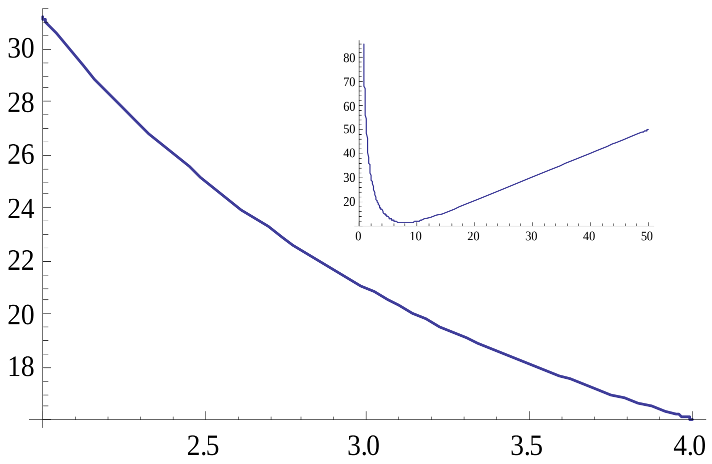

Fig.3 – Simulation for the pulse stretching by a martinez type with f=50mm, Lg=30mm, Xaxis -> Input FWHM, Yaxis=output FWHM. Extended scale in the inset.

Effects of a long cavity on mode-locking

The numbers resulting from dispersion management simulations yield a constraint for the cavity to length. In fact, to include two martinez type elements providing the desired GDD, the cavity length would range between 1 and 2 meters.

It makes sense to figure out the implications of such a long external cavity when the laser is driven in mode-locking regime.

A first effect we expect is a huge increase in peak intensity, due to the larger number of modes within the same bandwidth. In fact, considering the intensity of N phase-locked cavity modes are separated by multiples of the free spectral range w, we have:

$$I_{peak} = \lim_{t \to 0} \frac{\sin^2(\frac{N\omega t}{2})}{\sin^2(\frac{\omega t}{2})}$$

The number of phase locked cavity modes times their distance is the gain bandwidth BW, which does not depend on the cavity length. Therefore

$$I_{peak} = \lim_{t \to 0} \frac{\sin^2(\frac{BWt}{2})}{\sin^2(\frac{\omega t}{2})} = \frac{BW^2}{\omega^2}$$

It is straight that increasing the cavity length decreases linearly the FSR, and thus increases quadratically the pulse energy.

However, increasing the cavity length to the meter level, triggers another problem that must be taken in account, if we aim to active modelocking. The time it takes for the pulse to go through the gain medium is much shorter than the round trip time. This is clearly shown in fig.4.

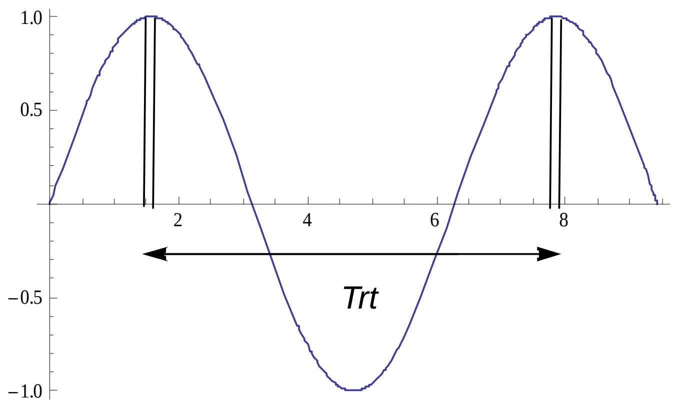

Fig. 4. In a long eternal cavity the round trip time Trt is much longer than the pulse transit time in the gain medium (between black bars)

In this circumstance, when modulating the cavity gain with a sinusoid at FSR frequency, the gain medium continues to be pumped also when the pulse has already transited, allowing for the formation of multiple secondary pulses at random times. This mechanism may destabilize modelocking in a few roundtrips.

In addition, from Haus master equation, the temporal pulse-width in active mode-locking scales inversely with the square of the second derivative of the modulating function in its apex point. In case of sinusoidal modulation we have:

$$\Delta t = \sqrt[4]{\frac{g}{\Omega_g^2 m \omega_m^2}} \approx \frac{1}{\sqrt{\omega_m}}$$

Where g is the unsaturated gain, Ωg is the width of the gain bandwidth, m and ω_m are respectively the modulation amplitude and frequency. Since the modulation in active mode locking is at the FSR frequency, extremely long cavity yields a small FSR, and therefore extremely broadened pulses.
Two different solutions Have been proposed to overcome this drawback.

Active modelocking with custom waveform modulation

One proposed solution solution could consist in driving the gain with the sum of N phase-locked harmonics of the cavity free spectral range frequency (FSR), rather than a single sinusoidal signal. This modulating function allows simultaneously to reduce to 1 the ratio between the gain medium pumping time and the round trip time, whithout reducing the pulse energy as in harmonic mode locking.
Modulating the gain with a waveform like

$$f(t) = \sum_{i+1}^{N} \cos(i\omega_{FSR} t)$$

with N=10, has the same apex curvature than a single sinusoid at FSR 7th harmonic (considering equal amplitudes, like in fig. below). This slightly smaller curvature can be compensated for by adding a few more harmonics. This is feasible since in a meter-length cavity the 10th harmonic is only a few GHz..

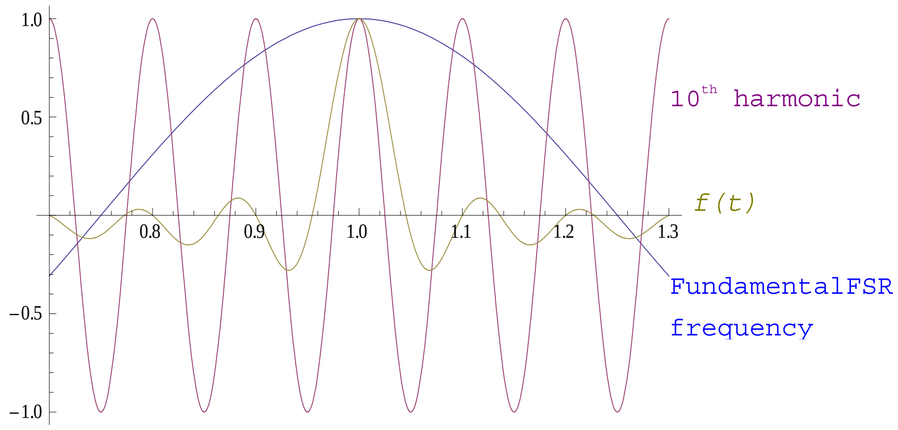

Fig.5 – comparison among different modulating functions in active mode locking: fundamental mode locking (blue), 10th harmonic modelocking (red), proposed waveform (gold)

On the other hand, with the f(t) function the modulating period is the round trip time: we get only one pulse circulating in the cavity. The intracavity energy is not shared between N pulses, and also the fundamental repetition rate is preserved. In a way it can be seen like a q-switch that preserves the sideband interaction in the frequency domain, which is required for mode-locking.

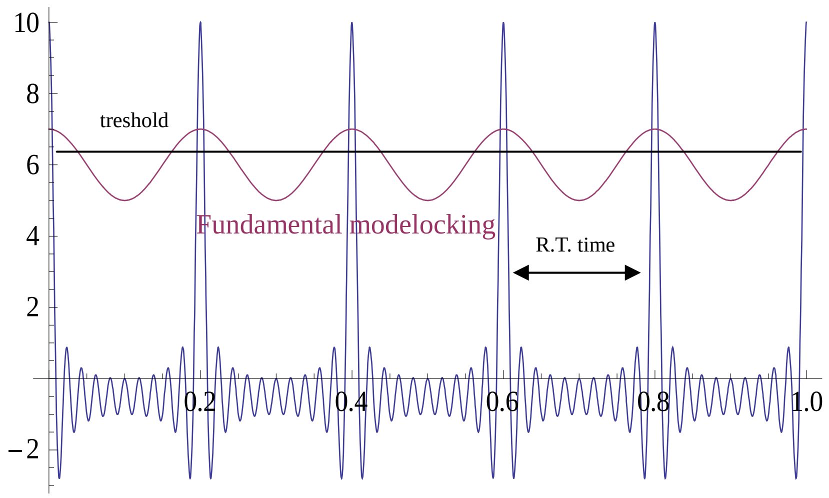

Fig.6 – principle of waveform mode locking.

Passive modelocking with tunable saturable absorber

A saturable absorber (SA) with ultrafast recovery time could also be used in order to quickly shut the low-loss window, after the modelocked pulse has passed, thus blocking any other random spiking. However, there are two main problems. First, no saturable absorber is commercially available at 8 microns wavelength, and in addition, it is not possible to foresee what saturation fluence is needed for our application. These considerations triggered the idea of using the quantum well engineering facilities of Capasso group to project a semiconductor saturable absorber with tunable saturation fluence in the mid-infrared.

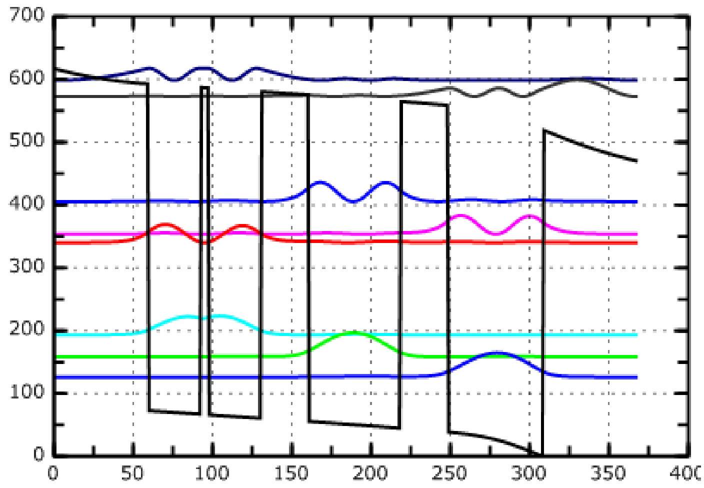

Fig.7 – Etherostructure planned for the tunable saturable absorber at 8 microns.

The basic structure alternates InAlAs (barriers) and InGaAs (wells) layers as shown in fig 7. The width of each layer is planned in order to have an intersubband transition tuned to absorb at 8.4 microns (around 150mEV). Such a strong absorption occurs between level 3 (cyan) and level 4 (red). The SA fast recovery time is ensured by the lifetime of level 4, which is 500fs, while the saturation fluence depends essenctially on the number of electrons present in level 3. Now, population of level 3 can be controlled by applying a bias voltage to the entire structure. This is shown in fig. 8.

For high, positive applied field (frame 1, 30 KV/cm)electrons tend to populate mostly level 1 which has the lowest energy, while only a few electrons may be scattered to level 2 and to level 3 by phonon collisions. As the field is depleted and change sign, the energy gaps between levels 1,2,3 tend to zero. In this circumstances, the larger(negative) is the field, the more efficiently electrons can be scattered and populate level 3.

On the right side of fig.8, the simulated absorption spectra of this structure with scaling applied voltage is shown, demonstrating that the absorption coefficient at 8.4 microns can be tuned by an entire order of magnitude order of magnitude by tuning the bias voltage from 30KV/cm to -60KV/cm.

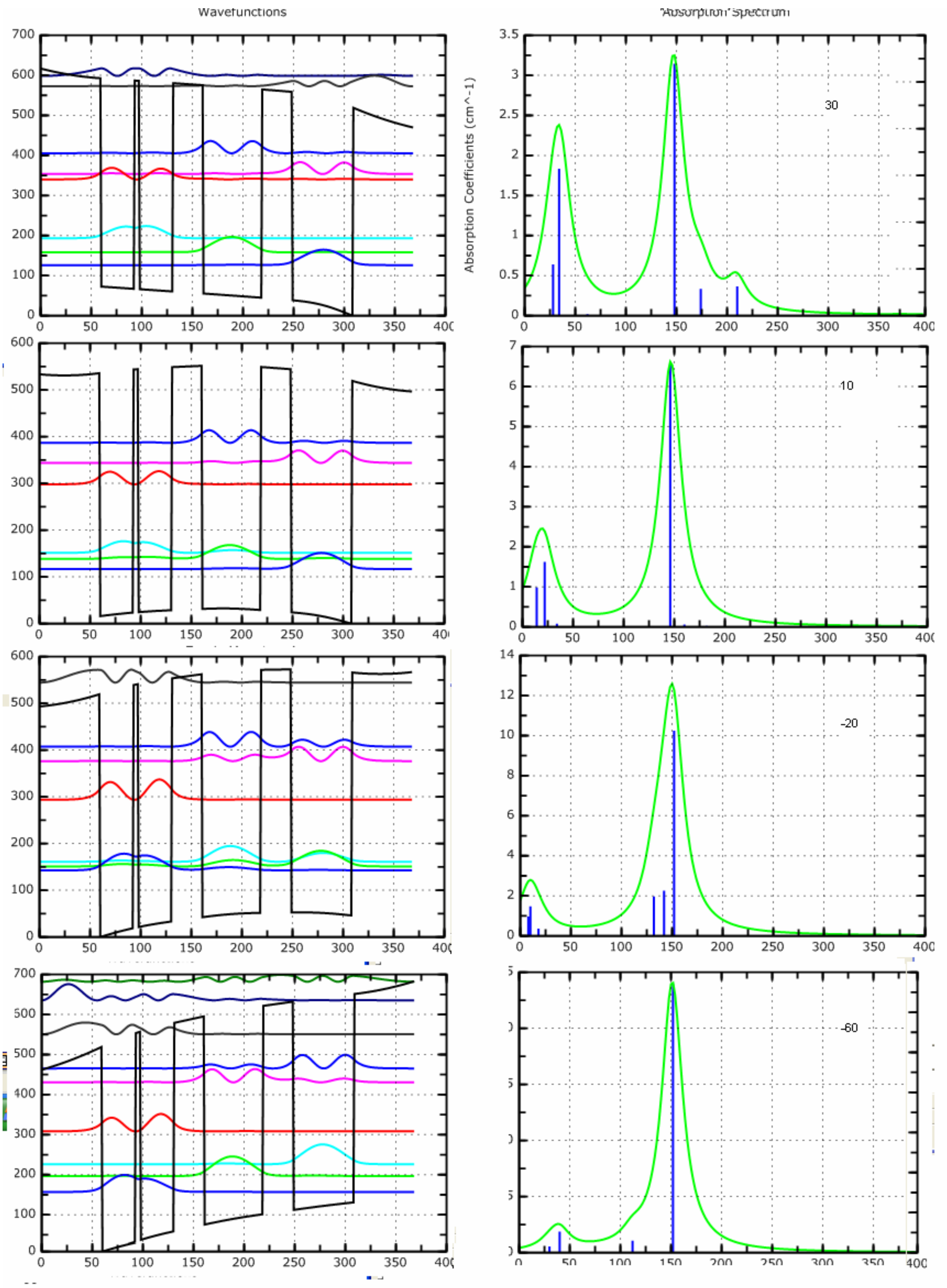

Fig.8 – Tuning the absorption coefficient of the etherostructure with an applied bias voltage. Left Energy band diagrams for different c\values of the electric field (indicated on the right). Right: correspondent calculated absorption spectrum