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Active Mode Locking of a High Pressure CW Waveguide CO_2 Laser

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Abstract. In this paper, we report on a new concept for active mode locking of lasers. It has been successfully applied to a cw waveguide CO_2 laser and pulse widths as short as 2 ns have been obtained.

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During recent years, a large amount of investigations has been devoted to laser mode-locking techniques. In the visible range, this effort has resulted in femtosecond pulses generation, making possible a large range of studies including time resolved spectroscopy, electric signal switching or sampling, ultra fast shutter.

In the infrared spectrum, it is possible to obtain subnanosecond pulse widths by using TEA CO_2 laser. In the cw regime, a few number of experiments have been reported. Using switching technique, induced by cw visible mode-locked lasers, one has obtained picosecond pulse widths [1]. On an other hand, direct mode-locked infrared laser has been achieved using pressure broadened CO_2 waveguide laser and amplitude modulation induced by an acousto-optic modulator. In this paper, a new technique will be reported in which waves with frequencies corresponding to the longitudinal modes of the laser are generated by an acousto-optic frequency shifter set up in the laser cavity and phase shifted by two secondary cavities coupled to the laser cavity by the acousto-optic modulator.

1. Experimental Apparatus and Principle

The experimental apparatus is shown in Fig. 1. It consists of two crossed cavities. The main cavity involves a CO_2 waveguide amplifier. This amplifier is made of six BeO tubes 12.5 cm in length and 1.5 mm in internal diameter. These tubes are mounted on six water-cooled holders kept in line by three INVAR rods. Machining of the holders was carried out with great care in order to insure the proper mechanical alignment of the guides. A gas mixture CO_2; N_2; He(15; 15; 70) is flowing from the center of each section to its ends and a double discharge for each tube supplies the electrical pumping. The ends of the guide are closed by two Brewster windows. One end of the cavity is coupled to the output mirror M_0 using a geometry able to minimize the coupling losses [3]. The other end is coupled to an anti-resonant cavity using two lenses L_1 and L_2, with a configuration also fitted to cancel the coupling losses [4]. At the center of the anti-resonant cavity an acousto optic modulator (AOM) was installed making it possible to couple the main cavity to the cavity shaped by the two spherical mirrors M_1 and M_2.

Let us call ν_0 the frequency oscillating in the main cavity when the AOM is switched off. Because of the homogeneous broadening, only one mode reaches the oscillation threshold. When the AOM is driven at frequency $\delta\nu$, a part of the light travelling in the anti-resonant cavity is frequency shifted of an amount of

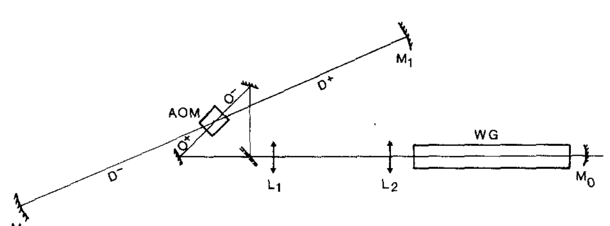

Fig. 1. Experimental apparatus (AOM: Acousto-optic modulator, WG: Waveguide amplifier, M_0: output mirror)

$\pm\delta\nu$ following the direction of the light with respect to the acoustic wave vector and directed to the mirror M_1 or M_2. The radius or curvature of these mirrors have been chosen in order to image the beam waist located at the center of the AOM onto itself with unity magnification coefficient. A part of each returning beam is then injected in the main cavity with frequencies $\nu_0 \pm 2\delta\nu$ and amplified in the waveguide amplifier. The amount reflected by mirror M_0 generates new components at frequency $\nu_0 \pm 4\delta\nu$ following the same scenario.

It is thus possible to synthetized a series of beams at frequencies $\nu_0 \pm (2n\delta\nu)$ in the main cavity and stored beams at frequency $\nu_0 \pm (2n+1)\delta\nu$ in the M_1M_2 cavity. The maximum value of the integer n depends upon the amplifier bandwidth (gas pressure, losses and gain amplifier) and the finesse of the cavity M_1M_2 (loss, mode coupling, AOM efficiency).

Let us assume that all cavities have equal round trip lengths L and that $\delta\nu$ is equal to $c/2L$. The various waves at frequency $\nu_0 \pm nc/L$ correspond to the main cavity modes and are thus emerging in phase from the mirror M_0. Then the beat of them builds up shorts pulses.

2. Experimental Results

In Fig. 2 a train of pulses obtained with such a technique is shown. In this experiment the reflectivity of M_0 was 0.9 and the pressure in the waveguide amplifier was 140 Torrs providing a 700 MHz full width at half maximum (FWHM) of the pressure broadened gain [5]. The shape of an individual pulse shown in Fig. 3 exhibits a 2.3 ns (FWHM). The detector used for this record is a HgCdTe uncooled photoconductive detector LABIMEX R006, the response time of which is 350 ps. The electrical signal was monitored on a 7104 Tektronix oscilloscope using a 7A29 amplifier. Such an apparatus provides a response time of 350 ps. In Fig. 4, the frequency spectrum of this train of pulses is shown.

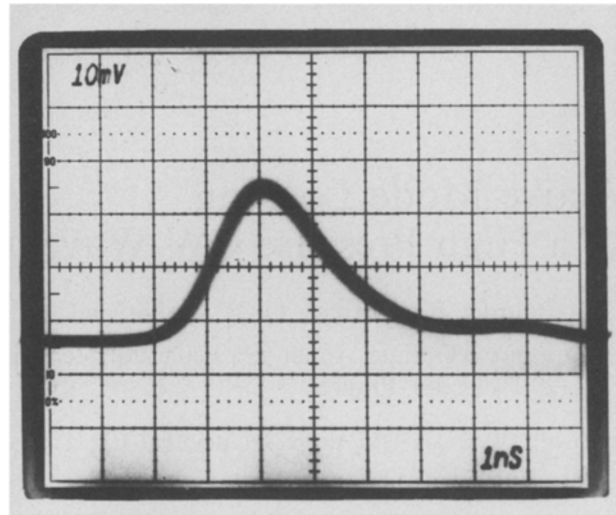

Fig. 3. Pulse shape exhibiting a 2.3 ns (FWHM)

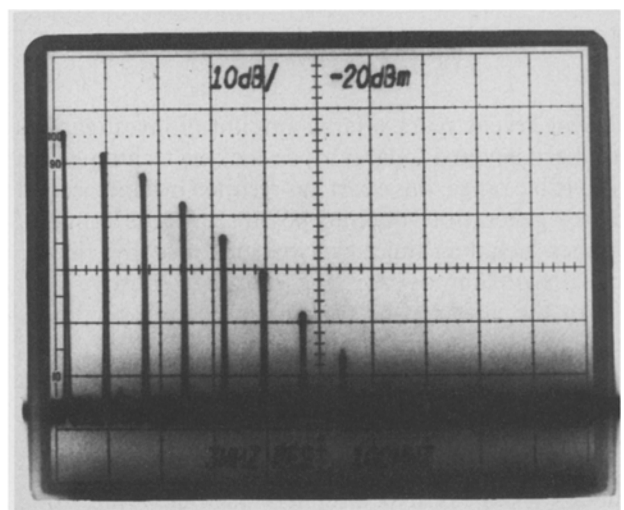

Fig. 4. Frequency spectrum of the pulse train shown in Fig. 2. The frequency interval between two adjacent modes is 75 MHz

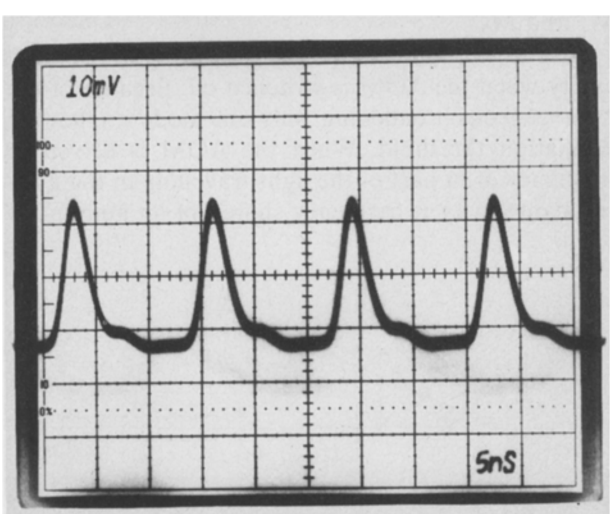

Fig. 2. Pulse train obtained with a 0.9 reflectivity output mirror

In a second experiment, we have tested the same quantities using a 0.99 output mirror reflectivity. Since the averaged output power decreased from 1.8 W to 90 mW, the FWHM was only reduced down to 2 ns while the frequency spectrum is extended up to 750 MHz. In this experiment, the optimum mixture pressure, with regard to the pulses FWHM, was 180 Torr corresponding to a 900 MHz FWHM of the gain. The optimum rf power driving the AOM (ISOMET

1207B) was 30 W instead of 16 W when a 0.9 reflectivity coupling mirror was used.

3. Discussion

A careful examination of the experimental arrangement reveals the following.

At first, the round-trip loss induced by the guide, the lens L_1 and L_2 and the unactivated AOM has been measured equal to 0.4. After, the antiresonant cavity is a source of extra losses in the configuration used.

Indeed, let us call A_m^+ and A_n^- the amplitude of the waves at frequency $\nu_0+2n\delta\nu$ being incoming and reflected by the antiresonant cavity following the axis of the laser cavity (Fig. 5). These two amplitudes may be coupled following the equation

$$\begin{aligned}A_n^- &= \varepsilon\cdot\tau\cdot A_n^+\exp[-ik_n(l^+ + l^-)]\\ &+\frac{1}{2}\cdot\frac{\varrho^2\exp(-ik_nL)}{1-\tau^2\exp(-ik_nL)}\\ &\times(\varepsilon A_{n+1}^+\{\tau\cdot\exp[-i(k_{n+1}l^- + k_ul^+ + k_nL)]\\ &+\exp[-i(k_{n+1}+k_n)l^-]\}\\ &+A_{n-1}^+\{\exp[-i(k_{n-1}+k_n)l^+]\\ &+\tau\cdot\exp[-i(k_{n-1}l^+ + k_nl^- + k_nL)]\}), \qquad (1)\end{aligned}$$

where k_n is the wavenumber of the wave oscillating at frequency $\nu_0+2n\delta\nu$, l^+ and l^- are the lengths separating the AOM to the beam splitter following the two ways l^+ and l^-, L is the round-trip length of the secondary and main cavities, ϱ is the amplitude efficiency of the AOM, $\tau=t\sqrt{1-\varrho^2}$ where t is the amplitude transmission coefficient of the AOM and ε is ± 1 following the direction of the beam splitter with respect to the incoming wave.

The transmitted wave amplitude B_n at frequency $\nu_0+2n\delta\nu$ leaking from the antiresonant cavity may be expressed as

$$\begin{aligned}B_n &= \frac{1}{2}\cdot\frac{\varrho^2\exp(-ik_nL)}{1-\tau^2\exp(-ik_nL)}\\ &\times(A_{n+1}^+\{\tau\cdot\exp[-i(k_{n+1}l^- + k_nl^+ + k_nL)]\\ &-\exp[-i(k_{n+1}+k_n)l^-]\}\\ &+\varepsilon A_{n-1}^+\{\exp[-i(k_{n-1}+k_n)l^+]\\ &-\tau\cdot\exp[-i(k_{n-1}l^+ + k_nl^- + k_nL)]\}). \qquad (2)\end{aligned}$$

Two conditions are required in order to cancel B_n as it is expected in a conventional anti-resonant cavity. At first, $A_{n+1}^+=A_{n-1}^+$. This condition is only satisfied for $n=0$ when ν_0 is the frequency at line center. Then,

$$(k_{n+1}+k_n)l^- = (k_{n-1}+k_n)l^+ + 2K\pi, \qquad (3)$$

$$\begin{aligned}&(k_{n+1}l^- + k_nl^+ + k_nL)\\ &=(k_{n-1}l^+ + k_nl^- + k_nL)+2K'\pi. \qquad (4)\end{aligned}$$

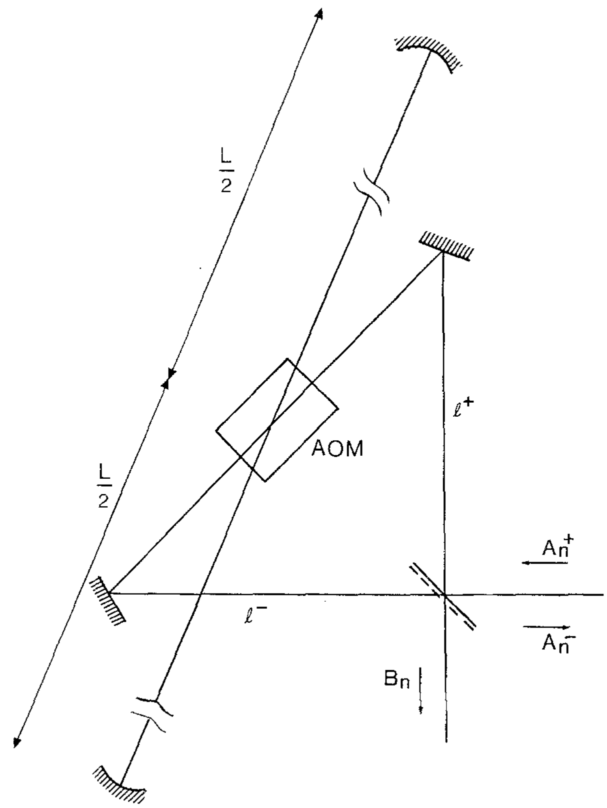

Fig. 5. Detailed design of the antiresonant cavity

Both these two equalities may be verified if

$$L=l^+=l^-. \qquad (5)$$

Since

$$k_n\cdot L=2N\pi\ \forall n. \qquad (6)$$

In our experiment, considering the 40 MHz resonance frequency of the conventional infrared commercially available AOM, the round trip cavity length L must be equal to 3.75 m. The optimal arrangement thus leads to a very extensive set up. Instead of this solution, the lengths $l^\pm$ have been chosen as short as possible (36 cm) in order to minimize the propagation change of phase $k_n l^\pm$.

Since the relative change of phase undergone by two adjacent longitudinal modes over one round trip in the cavity (3.75 m) is equal to 2π, this change of phase over the 36 cm separating the AOM to the beam splitter is equal to about 35°. As a result, about 5 W corresponding to not in-phase modes are transmitted by the beam splitter while only useful 1.8 W are emitted by the laser. Therefore, lowering the output mirror transmission does not significantly change the round-trip loss so that the amplification of high-order modes is not greatly improved.

This effect also appears on the resonance frequency of each mode. Instead of the frequency modulation equal to 40 MHz as it would be expected when a 3.75 m round-trip cavity length is used, the optimum driving frequency for the AOM has been experimentally found to be 37.5 MHz for $R=0.9$ and 38.5 MHz for $R=0.99$. This discrepancy cannot totally be explained by the dispersion induced by propagation through the amplifier medium.

Nevertheless, we find that, for a given amplifier bandwidth, the pulse width is shorter than that reported in [2]. In this reference, a standing wave acousto-optic modulator set up inside the laser cavity generates modulated losses and consequently lateral frequency components. In opposition, in our arrangement the amount lost by the AOM is re-injected in the amplifier medium. Then, if all the cavities lengths are properly chosen, no additional losses are generated by the AOM switching on.

On an another hand, one may evaluate how difficult it is to set up a 3-cavity laser with respect to the advantageous pulses shortening carried out. In our actual arrangement, no particular difficulties arose for alignment. The angular location of the mirrors bounding the two secondary cavities may be easily performed when the main cavity oscillates without mode-locking and the pulse width was not found to be sensitive upon their longitudinal location. However, if we take into account that the angular and longitudinal mismatching are connected to the losses induced in the laser cavity, we expect that misalignment error would be more sensitive for an apparatus exhibiting lower loss and, thus, able to synthetize shorter pulses.

4. Conclusion

A new design of an active frequency mode locked laser has been successfully checked. In this experiment, an acousto optic frequency shifter set up in the cavity of a homogeneously pressure broadened CO_2 waveguide laser makes it possible to couple the laser cavity to two secondary cavities. This apparatus, properly adjusted, generates new waves, frequencies of which correspond to the longitudinal laser modes leading to short pulses synthesis. Full width at half maximum pulses as short as 2 ns have been obtained. A critical survey of the options chosen has shown the limit of our experimental set up and that sub nanosecond pulses may be expected by changing the configuration of the cavities. Investigations of new arrangements are now in progress.

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