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High-Frequency Modulation of a Quantum-Cascade Laser Using a Monolithically Integrated Intracavity Modulator

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***Abstract*—We report a quantum-cascade laser monolithically integrated with an intracavity modulator which could be operated up to 1 GHz. In contrast to earlier approaches, where the radio frequency (RF) modulation signal was supplied to the entire cavity length of the laser structure, we drive only a relatively small 375-μm-long section of the cavity. At the same time, a quasi-continuous-wave signal was supplied to the remaining 1125-μm-long section. This modulation scheme resulted in smaller parasitic capacitance effects than what we reported previously, and enabled us to work with lower RF voltages and currents.**

***Index Terms*—Atmospheric window, free-space, intracavity modulator, optical data transmission, quantum-cascade (QC) laser.**

AFTER a period of tremendous progress, which culminated in the demonstration of room-temperature continuous-wave operation [1], mid-infrared quantum-cascade (QC) lasers are now mature enough to enter various fields of applications. These applications range from spectroscopy via process monitoring to free-space optical telecommunication [2]–[5]. QC lasers will be especially suitable for optical data transmission on the last mile, where the transmission bandwidth has so far been limited by the use of copper wires. Compared with this existing technology, QC lasers with modulation frequencies of 1–5 GHz would already correspond to a bandwidth improvement of nearly two orders of magnitude. For such telecommunication systems, it is, therefore, quite crucial to reduce, wherever possible, parasitic capacitance effects by shrinking active device size. In the past, QC lasers have been modulated directly at frequencies of up to 7 GHz and at cryogenic temperatures [6]. However, this modulation technique might become impractical when going to higher temperatures. The main reason is that QC lasers tend to have substantially larger threshold currents at 300 K than at low temperatures. Together with the typical QC operating voltage of 8 V, those high currents might be rather difficult to be directly modulated; in addition, the relatively large area of such a device typically leads to parasitic capacitance effects which will ultimately limit the maximal modulation speed. For this reason, we propose and implement, here, a prototype of a solution based on a two-section QC laser with a monolithically integrated intracavity modulator, similar to that described for a near infrared diode laser in [7]. While the longer section is operated in quasi-continuous-wave operation, a radio frequency (RF) signal is supplied to the short section. This has the advantages that the currents to be switched are smaller and that the capacitance of the short section is only a fraction of the one corresponding to the full length laser cavity. In a first test using such an intracavity modulation, we succeeded to modulate the laser at 1 GHz, and observed an ON–OFF ratio of 4 dB.

All experiments described in the following were carried out on a graded interface laser structure emitting mid-infrared radiation at a wavelength of 9 μm. The active region of this laser consisted of 35 repetitions of a period which was basically identical to the one published in [1]. The only difference was that the four barriers and wells of the gain region had digitally graded interfaces. Here, digitally graded means that each sharp interface between an $In_{0.53}Ga_{0.47}As$ well and an $In_{0.52}Al_{0.48}As$ barrier and its neighboring ±3 Å was replaced by a 1 Å $In_{0.52}Al_{0.48}As$–2 Å $In_{0.53}Ga_{0.47}As$–2 Å $In_{0.52}Al_{0.48}As$–1 Å $In_{0.53}Ga_{0.47}As$ interface. Details on the overall performance of this laser structure will be published elsewhere. The InP substrate and a 3-μm-thick metal–organic vapor phase epitaxy regrown InP layer on the top served as low-loss cladding layers. Growth of the $In_{0.53}Ga_{0.47}As$ waveguide layers and the active region was based on molecular beam epitaxy. A 28-μm-wide ridge waveguides were fabricated by standard processes like chemical wet etching, Si_3N_4 passivation, sample thinning, and contact metallization. Laser facets were generated by cleaving the sample into 1.5-mm-wide bars. These laser bars were left uncoated and soldered junction-up on copper heatsinks. Using photolithography, the top metallization was divided into two sections with respective lengths of 1125 and 375 μm; both of them could be contacted individually. Given the separation between the two metal contacts (30 μm), the thickness (0.5 μm), and the doping level of the top contact layer (5×10^{18} cm^{-3}), only negligible crosstalk occurred. A similar observation was made by Rochat *et al.* when measuring the waveguide loss of QC lasers using a multisection cavity technique [8]. The laser was mounted in a liquid N_2 flow cryostat and cooled to 77 K. For high-frequency modulation experiments, 10-μs-long bursts of RF pulses were supplied onto the short section of the laser. We produced these RF pulses with a gated MARCONI 2022 pulser which delivered up to 3-dBm RF output power at a maximum frequency of 1 GHz. The pulses were amplified using a 48-dB power amplifier and fed into a low-loss 50 Ω coaxial cable (Huber–Suhner RG213U). During

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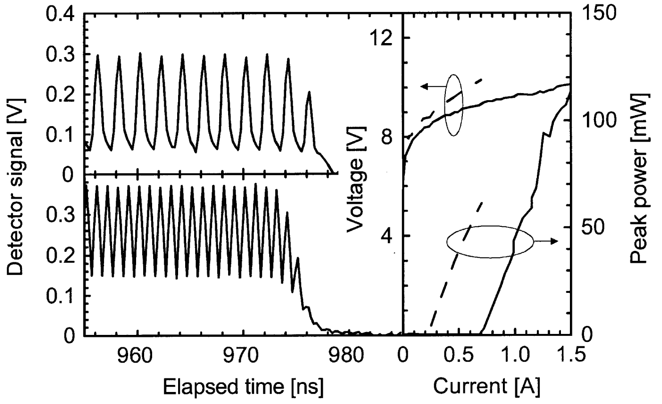

Fig. 1. (top left) RF modulation of a QC laser at 500 MHz. 1-μs-long current pulses with an amplitude of 495 mA were injected into the long section, while a 10-μs-long stream of RF pulses reached the short section. (bottom left) The same experiment but at 1-GHz RF frequency. (right) The solid lines represent a standard measurement of the *L–I–V* curves. For the dashed lines, 700-ns-long current pulses of 495 mA (0.97 j_{th}) were injected into the long cavity section. At the same time, the short section received 100-ns long pulses.

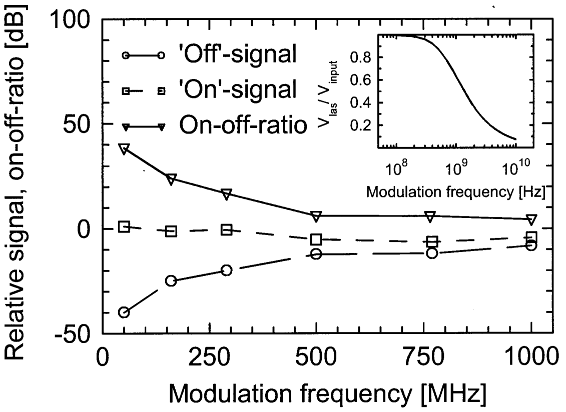

Fig. 2. "ON" and "OFF" values and ON–OFF ratio as a function of modulation frequency for the same device as in the previous figure. The inset shows the ratio between the differential voltage drop on the laser and the input voltage as a function of frequency.

the RF bursts, we injected 1-μs-long constant current pulses of 100-Hz frequency into the long laser section. The current density in the long section was adjusted around threshold. As soon as the amplitude of the RF bursts was sufficiently large, the laser would turn ON. The laser beam was collected with f/0.8 optics and focussed onto a small room temperature HgCdTe detector with a maximal bandwidth of 2.5 GHz (VIGO Systems PEM-L-3). The signal of the latter was amplified by a 2.5-GHz preamplifier (Sonoma Instruments) and connected to a digital oscilloscope (LeCroy LC564DL).

In Fig. 1 (right), we present a pair of light output–current–voltage (*L–I–V*) curves measured at 77 K. The two solid lines correspond to the experiment with the two sections being electrically connected; i.e. the entire laser receiving the same current density. The dashed lines show the device behavior with the long section pumped close to threshold, while the current was varied only in the short section. For the first configuration, we observed a threshold current of 680 mA, which corresponds to a threshold current density of 1.62 kA/cm^2. The second experiment shows that, together with the long cavity section being close to threshold, only an additional 185 mA $(j_{\text{th}} = 1.76\ \text{kA/cm}^2)$ was required to bring the entire laser above threshold. A modified formula for the threshold gain $g_{\text{th}}L_{\text{tot}} = g_1L_1 + g_2L_2$, and the fact that the ratio of the threshold current densities was larger than unity, indicate that in the second experiment the long cavity section was even slightly below threshold $(j_{\text{long}} = 0.97\ j_{\text{th}})$. The slope efficiencies obtained from the first and the second measurement were 0.135 and 0.145 W/A, respectively. The almost identical results are expected because, in the two-section laser, only 25% of the cavity is used to produce optical output power. However, the resulting smaller output power is also divided by a smaller current. The differential resistance at threshold increased from about 1 Ω when pumping the whole cavity to a value of 4–5 Ω when pumping only the short section.

For the RF experiment, which was carried out at nominally constant RF power levels, we varied the modulation frequency on the short section between 50 MHz and 1 GHz while the long section always received, as in the previous measurement, the same current of 495 mA (0.97 j_{th}). In the upper half of Fig. 1 (left), we present a measurement of the detected signal versus time at a modulation frequency of 500 MHz. An ON–OFF ratio of 7 dB was observed. The lower half of Fig. 1 (left) shows the equivalent measurement at a modulation frequency of 1 GHz. In this case, the ON–OFF ratio decreased to 4 dB. The somewhat counter-intuitive increase of the maximal signal at higher frequency could be an artifact due to multiple reflections in the long 50 Ω line between the power amplifier and the laser. However, based on the observation that the "OFF"-signal increased with increasing frequency, we believe rather in an ac-to-dc conversion due to the nonlinear *I–V* characteristic of the laser. This is illustrated in Fig. 2, where we present the laser's ON–OFF ratio, and its "ON" and "OFF" signals in function of the modulation frequency. As expected, the signal's ON–OFF ratio decreases at higher frequency, indicating that the laser's parasitic capacitance starts to come into play, and that some of the components in the present measurement setup are operating too close to their bandwidth limit. One of these components is the oscilloscope which has its 3-dB bandwidth at 1 GHz. In addition, the 10-m-long transmission cable between the power amplifier and the cryostat has only 0.43-dB attenuation at 50 MHz, but already 2.4 dB at 1 GHz. Given also the attenuation behavior of the coaxial cable in the cryostat, we estimate available RF voltages of about ±56 V $(V_{\text{pp}} = 112\ \text{V})$ at 50 MHz, but only ±28 V $(V_{\text{pp}} = 56\ \text{V})$ at 1 GHz. Assuming perfect impedance matching in the cryostat, the modulator section should have seen currents of roughly ±1.12 A at 50 MHz and ±560 mA at 1 GHz. A closer look at Fig. 1 shows that these currents on the short cavity section would be largely sufficient to bring the entire laser above threshold.

Based on the responsivity of the detector $R = 0.6\ \text{V/W}$ and the characteristics of the preamplifier, we determined the output power of the device at different modulation frequencies. This procedure yielded values of 28 mW peak power at 50 MHz and 7 mW at 1 GHz. Since the above mentioned modulation currents are, in principle, large enough to produce at least 80 mW output power for 50 MHz and still about 40 mW at 1 GHz, we can already anticipate that a quite serious capacitance problem must have been present in this experiment. This becomes evident if we compare estimated RC time constants of the present device and the one from our recent publication [5], where we reported direct modulation of a 3-mm-long QC laser at a frequency of 350 MHz. Its parasitic capacitance was as large as 150 pF, but the RF voltage was supplied via a 4 Ω low impedance line resulting in $\tau = 600$ ps. Here, the capacitance of the 375-μm-long modulator section decreased by roughly a factor of 8 (compared with the 3-mm-long laser), but at the same time, the series resistance increased by almost a factor of 12 to 47 Ω. Although this will result in a comparable or even slightly lower frequency limit, the use of 50 Ω transmission lines is, in general, certainly an advantage for high-frequency applications.

As Fig. 2 shows, the ON–OFF ratio, defined by $r_{\mathrm{on/off}} = 10 \times \log(I_{\max}/I_{\min})$ was reasonably high up to 290 MHz ($r_{\mathrm{on/off}} =$ 17 dB), dropped to 7 dB at 500 MHz, and finally settled at a value of $r_{\mathrm{on/off}} = 4$ dB at 1 GHz. Based on the fact that a parasitic capacitance determined the frequency limit of the entire experiment, we simulated the behavior of the QC laser using a simplified equivalent circuit. The QC laser itself was modeled by a nonlinear device with a turn-ON voltage of 8 V, a maximal current of 0.7 A, and series resistances of 1 $M\Omega$ and 5 Ω before and after turn-ON, respectively. This element was put in parallel with a capacitor of yet unknown capacitance, C_{las}; and finally, a resistor of 47 Ω in series with the two former elements completed the circuit. The latter was driven by an ac voltage generator with variable frequency. In order to correctly explain the output power drop and the increase of the "OFF" signal, it was necessary to assume a parasitic capacitance of 50 pF. A simple estimation taking into account the geometry and the dielectric constant of the involved materials resulted in a value of 50–100 pF, which is in good agreement with the simulation. The inset of Fig. 2 shows voltage drop on the 5 Ω differential resistance of the laser (normalized to the input voltage) as a function of frequency. When pushing the frequency from 100 MHz to 1 GHz, the available voltage drops to about one half of its initial value, thereby reducing the modulator drive current from 0.7 to 0.3 A, and cutting the peak power from 50 to less than 10 mW (see right half of Fig. 1). Given the above result for C_{las}, it is clear that the maximum modulation frequency of this particular laser is seriously affected by its too large parasitic capacitance. However, once this problem is solved by changing the geometry of the contact pads, the modulation frequency can be pushed to higher values until other effects will be come into play.

When going to frequencies beyond a couple of gigahertz, the most prominent effect will be the fact that the optical intensity in the cavity can decrease only due to internal absorption. Since this is, as well, an exponential process requiring a certain cavity length and, hence, a certain time (times the speed of light within the material), a short intracavity absorber must absorb quite strongly in order to guarantee high-speed operation. Requesting an ON–OFF ratio of at least 20 dB requires pulse periods corresponding to roughly ten exponential time constants (five for rise and five for decay). A data rate of 1-Gb/s results, therefore, in a time constant of 100 ps. In a full cavity length modulation, this means that the necessary absorption is on the order of $\Delta\alpha = n/(c\tau) = 1$ cm^{-1} ($n = 3.4$ is the refractive index, c the speed of light). In our laser, we observe typically a gain–current density coefficient of $\mathrm{dG}/\mathrm{dj} = 20$ cm/kA; the ratio of the two quantities yields a minimal current density sweep of ± 50 A/cm^2. For 10 GHz, this sweep increases to ± 500 A/cm^2, which starts to be quite substantial. If we compare this result with the one obtained from the intracavity modulator geometry, then we see that the required absorption and, thus, the necessary current density increase by a factor of 4; however, since the modulator length is only 0.25 times the entire cavity length, the total current would remain the same as for full cavity length modulation. In the case of the intracavity modulator, the frequency limit is set by the fact that going to negative drive currents does not increase the absorption any more [9]. But given the fact that a small modulator area results in a smaller parasitic capacitance, we are confident that QC lasers using intracavity modulators have the potential to out-perform full-cavity modulated QC lasers.

In conclusion, we have presented a two-section cavity-modulation scheme for mid-infrared QC lasers. Although these experiments were done at low temperature, it is obvious that the same method will work also at room temperature. It will be necessary, however, to use shorter cavity devices and junction-down mounting. In addition, laterally smaller contact pads are required to reduce the parasitic capacitance.

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