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Quantum cascade laser tuning by digital micromirror array-controlled external cavity

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ABSTRACT

A quantum cascade laser (QCL) tuning mechanism based on an external laser cavity containing a Micro ElectroMechanical System (MEMS) spatial light modulator in the form of a two-dimensional digital micromirror array (DMA) is described. The laser is tuned by modulating the reflectivity of DMA micromirror pixels under computer control. The resulting functionality enables fast (<0.1ms switching time) digitally controlled random-access wavelength tuning, high-bandwidth wavelength modulation (~30kHz modulation rate), and stable wavelength locking of the laser output. With one or more QCL gain elements built into the cavity, it is possible to cover a wide portion of the mid-wave and/or long-wave spectral range with a single device. The fast wideband digitally controlled laser tuning technology described is applicable to other tunable laser including solid-state, diode, gas, and fiber lasers.

Keywords: laser tuning, digital micromirror array, quantum cascade laser, MEMS, MOEMS, laser spectroscopy

1. INTRODUCTION

Quantum cascade lasers (QCL) are well-positioned to gain wide acceptance in a broad range of applications in analytical spectroscopy due to their broad tunability in the mid-wave (MWIR) to the long-wave infrared (LWIR) spectral region, where “fingerprint” spectral signatures of a vast number of relevant analytes exist. Generally, fast highly sensitive detection of trace species represents a long-standing challenge for laser spectroscopy sensors. The range of spectroscopic applications of QCLs encompasses both *in situ* and standoff sensing, the latter growing in importance as the available output power of newly developed QCLs increases.

In this paper we present a digitally-controlled tunable QCL source in the LWIR region based on the use of an external cavity containing a spectral modulator in the form of an addressable two-dimensional micromirror array. An intracavity diffraction grating disperses the broadband output of the QCL gain element across the surface of the modulator, where individually addressable micromirrors reflect the desired wavelength back to the gain element, thereby closing the loop and making the selected wavelength oscillate in the cavity.

2. INSTRUMENT CONCEPT

Building upon the spectral modulation methodology developed for Dispersive Transform Imaging Spectrometry (DTIS), an area in which Spectral Sciences Inc. has made significant inroads towards advancing spectral sensing and spectral imaging[1-6], we have developed fast electronically controlled, random wavelength access laser wavelength tuning demonstrated on long-wave infrared (LWIR) QCLs. In this paper we present the design and operation of an external tunable cavity based on the use of a reflective spatial light modulator (SLM) to select and sustain laser oscillations at the wavelength(s) determined by the spatial pattern created at the SLM as a part of the laser cavity[7] (Fig. 1). We use a digital micromirror array (DMA) SLM manufactured as a silicon MEMS (Micro Electro Mechanical System) device. The gain element of the laser is a QCL chip anti-reflection (AR) coated at the facet facing the external cavity. By using a dispersive intracavity element, the QCL output is spectrally resolved at the surface of the DMA, where individually addressable micromirrors reflect the desired wavelength back to the gain element, thereby closing the loop and making the selected wavelength oscillate in the cavity (Fig. 1). In this way laser tuning, locking and modulation under fast digital control inherent to the DMA devices becomes possible. An added benefit of the DMA technology for spectral modulation is that the tuning mechanism contains no macro-scale moving parts, making it highly mechanically robust for field use.

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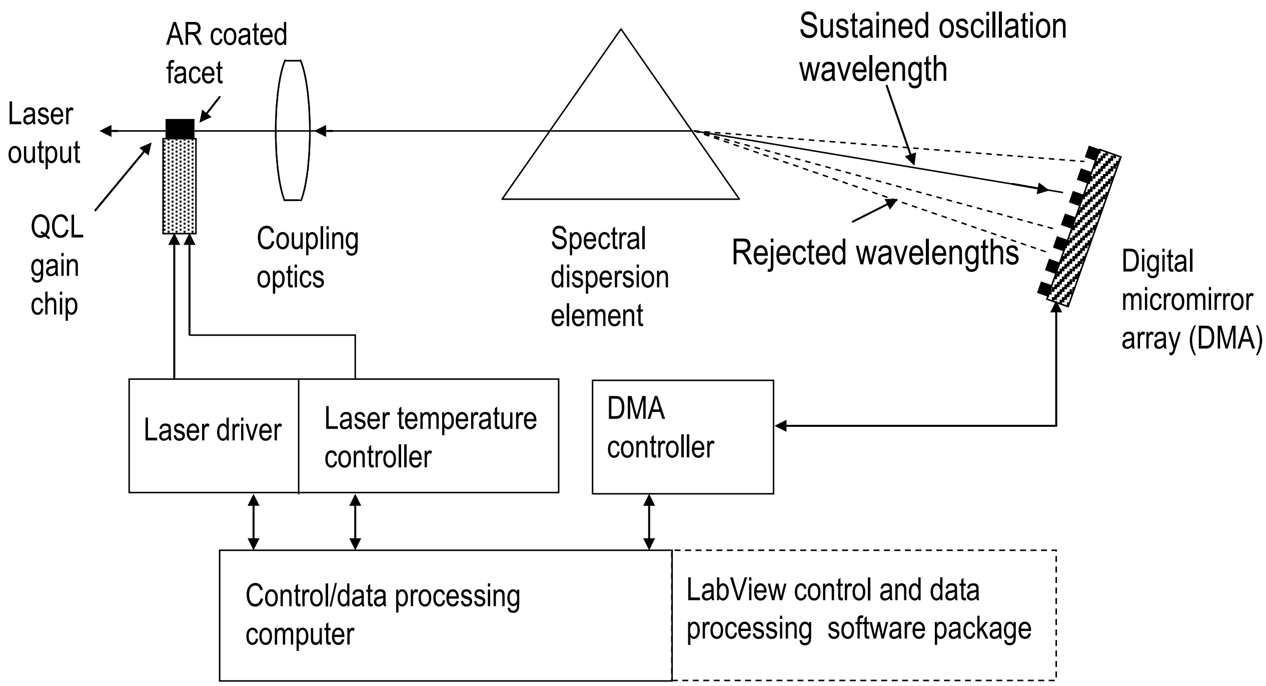

Figure 1. Digitally tunable quantum cascade laser concept.

3. INSTRUMENT DESIGN

Based on the principles outlined in the previous section, a tunable QCL using the external cavity shown on Fig. 2 was built. The cavity consists of a low-aberration wide-angle collection lens, a plane diffraction grating, and a DMA. The cavity was designed and optimized using the Zemax optical design package. The gain chip output is collected by a well-corrected 18mm focal length germanium F/1 lens (Scarlet series by Stingray Optics). Spectral dispersion is provided by a plane grating with 35 grooves/mm (Newport RGL model 33014FL02-934R). With these components, the optical system of Fig. 2 performs at the diffraction limit in the spectral range 7.8µm to 8.8µm, encompassing our tuning range of interest.

The DMA used in our system is Texas Instruments DMD 0.7 XGA 12° DDR device which selects the lasing wavelength by on-off switching the reflectivity of a 1024 x 768 array of addressable 14µm micromirrors. The original chip was modified by replacing the original visible-range window with a broadband AR-coated IR-transparent ZnSe window. Infrared-enabled DMAs were previously successfully used in our work on M/LWIR spectral imagers[1-6]. The intracavity DMA on Fig. 2 operates as a part of the DLI Discovery 4000 series (Digital Light Innovations, Inc.) development kit with the ALP 4.0 (ViALUX GmbH) high frame rate firmware. The modulation efficiency of a DMA with small 14µm mirrors can be optimized in the IR region by treating the DMA as a diffraction-based spatial light modulator acting as a grating, rather than a simple array of mirrors. The approach described previously[6] is based on generating the reflective area at the DMA in the form of a “checkerboard” pattern (every other micromirror turned off). At an appropriate angle, the modulation efficiency in the LWIR of 20% can be achieved this way, surpassing dramatically the efficiency of the mirror-reflection mode of operation.

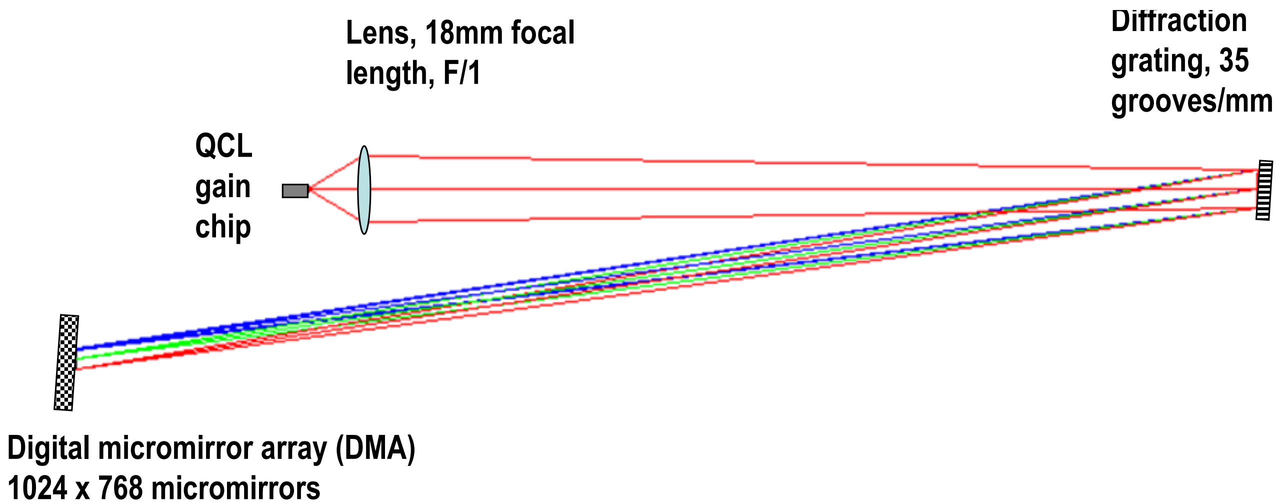

Figure 2. Tunable external laser cavity with a DMA spectral modulator.

Laser wavelength tuning is computer-controlled through a high-speed interface under the control of a program written in the LabView programming language (National Instruments Corp.). The laser tuning subroutines make it possible to tune and lock to the desired wavelength, to scan a spectral region, and to apply wavelength modulation involving any combination and number of wavelengths. The program controls the DLI Discovery 4000 board via its ALP firmware frame transfers. The software package (1) creates sets of checkerboard patterned reflective stripes of given width that can be positioned at any location on the DMA as well as scanned across; (2) implements a graphical user interface (GUI) that downloads the sets of stripes to the DMA and plays them in desired sequence at a user-controlled rate; and (3) provides for the wavelength calibration of stripes to be recorded and saved along with the stripes. The program makes it possible for multiple sequences to be downloaded to the DLI Discovery 4000 board and then selected and run on the DMA with a user-specified frame rate. The sequences are stored as a simple array of frame indices into a set of pre-computed frames. The LabView TDMS file format is used for storage in order to take advantage of its high-speed reading capability. An option exists to use pre-computed frames of fixed stripe width to avoid the high computational cost of calculating each frame every time a sequence is implemented.

4. EXPERIMENTAL RESULTS

Our electronically tunable QCL laser was demonstrated with gain chips produced by AdTech Optics (ATO). The chips were AR coated on one of the two facets, while the other facet was uncoated. The typical center wavelength was around 8.3µm. The tuning range of these chips was estimated by the manufacturer to be between $30cm^{-1}$ and $50cm^{-1}$ for typical grating-tunable external cavity operation. The laser injection current was supplied by the VueMetrix VUE-MV-14 laser driver. A VueMetrix Vue TEC temperature controller was used for laser cooling and temperature stabilization. Both the current driver and the temperature controller operated under computer control (Fig. 1). Laser output was monitored by a Teledyne Judson J15D14-M204-S02M 2mm square HgCdTe detector with a PA-101 preamplifier. The signal amplitude was typically measured by Tektronix TEK TPS 2024 digitizer with digital signal averaging.

The efficiency of external cavity coupling was tested first. The laser threshold was investigated by measuring the dependence of the laser optical output vs. the injection current, with and without the external cavity coupled to the gain chip. The results are presented in Fig. 3 for two of the chips used, CM7-W0983-1 and CM7-W0983-2. The two chips differ remarkably regarding their coupling efficiency. The CM7-W0983-2 chip shows 23% decrease of the threshold injection current when coupled to the external cavity relative to the threshold of the bare chip, indicating a good AR coating on the facet facing the cavity. The chip CM7-W0983-1, however, shows only 8% decrease in the threshold current when coupled to the external cavity, most likely due to the relatively poor AR coating on its facet. A similar spread in coupling efficiency data was found with several other ATO chips which were investigated.

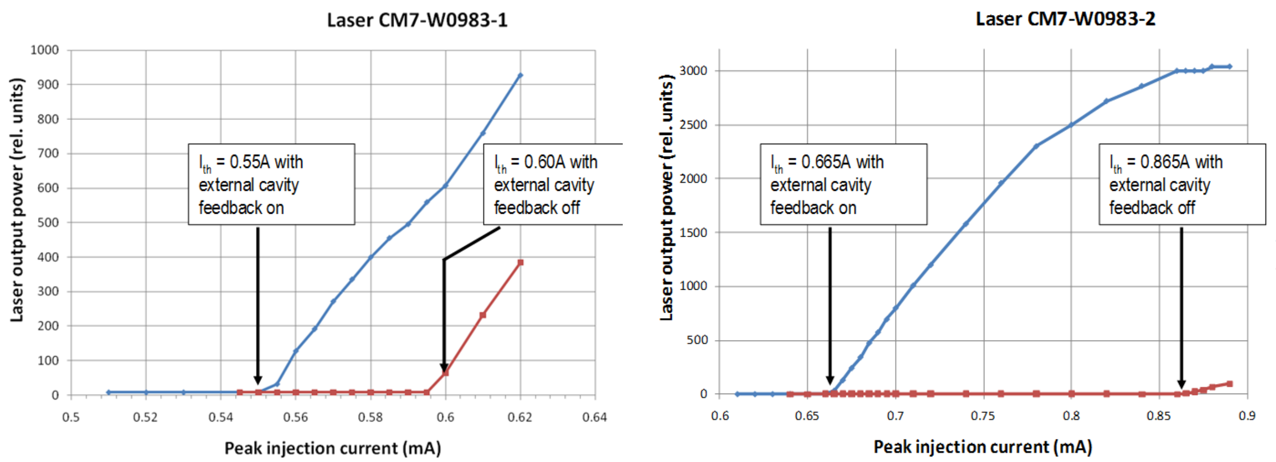

Figure 3. Laser output vs. injection current for two representative QCL gain chips, CM7-W0983-1 and CM7-W0983-2. Measured threshold currents with and without the external cavity feedback are indicated.

Wavelength tuning of our external-cavity QCL was investigated by using an FTIR spectrometer (Midac M4401S-E). The results showing the tuning range for two representative gain chips, both with relatively good AR coating, are presented here. The superimposed spectra of the laser output on Fig. 4 were obtained as the laser was tuned by the DMA control software which moved the reflective stripe across the DMA. Figure 4 (a) shows the spectral output of the tunable laser using the gain chip CM7-W0983-2 operated at the injection current of 0.85A, with the pulse repetition frequency of 30Hz and with 6ms pulse duration at the temperature of 17degC. Under these conditions, the average output power was 6.4mW, with the peak power of 35.2mW. The tuning range for this gain chip was found to be between 1189.7cm^{-1} and 1227.4cm^{-1} (8.15μm to 8.41μm) spanning 38cm^{-1} (0.26μm).

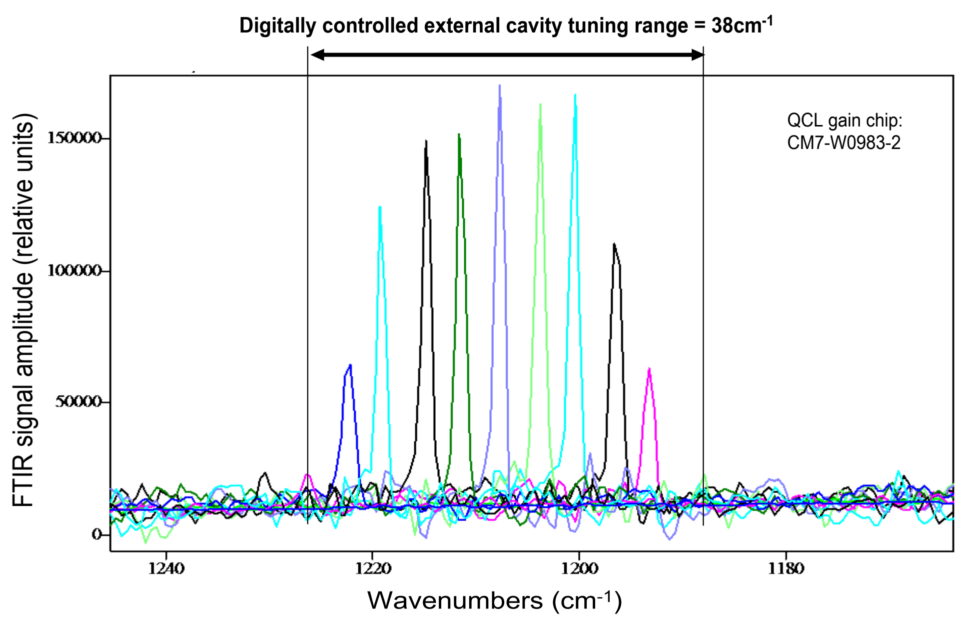

Figure 4 (a). The tuning curve for the CM7-W0983-2 chip showing tunability between 1189.7cm-1 and 1227.4cm-1 (8.15μm to 8.41μm) spanning 38cm-1 (0.26μm).

Figure 4(b) shows the tuning range measured for another gain chip, the CM7-12-CI0316. The laser was driven with pulse repetition frequency of 90Hz and with 3ms pulse duration at the temperature of 19degC. Under these conditions, the average output power of the laser was 5.5mW, with the peak power of 20.4mW. The laser containing this chip was tunable between 1173.0cm^{-1} and 1221.2cm^{-1} (8.18μm to 8.52μm) spanning 48.2cm^{-1} (0.34μm), significantly wider than that of the CM7-W0983-2 chip.

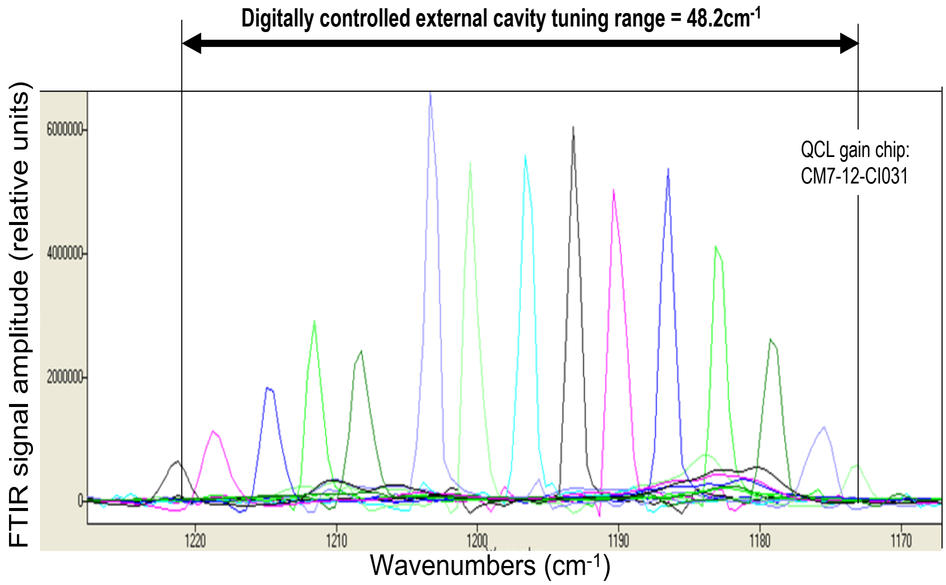

Figure 4 (b). The tuning curve of the CM7-12-CI0316 chip showing tunability between 1173.0cm-1 and 1221.2cm-1 (8.18µm to 8.52µm) spanning 48.2cm-1 (0.34µm).

The 48 cm^{-1} tuning range reported above, compared to the expected $30cm^{-1}$ to 50 cm^{-1}, shows that incorporation of a DMA in an external cavity does not decrease the extent of the QCL tuning range. It indicates efficient external cavity operation with strong coupling and low intracavity losses other than those associated with the efficiency of the DMA spatial modulator[6]. Compared to other external cavities, however, the use of the DMA provides the benefits that motivated this study: fast, purely electronic digitally controlled laser tuning and random wavelength access capability rather than sequential scanning. Regarding the laser linewidth, we found it to be smaller than the $0.5cm^{-1}$ spectral resolution limit of our Midac M4401S-E FTIR spectrometer.

6. CONCLUSIONS

Tunable QCL based on MEMS spatial light modulator as a tuning element in an external cavity has been demonstrated. The system is capable of providing fast (<0.1ms switching time) digitally controlled random-access wavelength tuning, high-bandwidth wavelength modulation (~30kHz modulation rate), and stable wavelength locking of the laser output. All these parameters are highly desirable for majority of laser spectroscopic sensors aimed at both *in situ* and standoff sensing of gaseous (e.g. atmospheric trace gases and pollutants) and solid state (e.g. surface contamination) detection.

The laser wavelength tuning range achieved with the described system appears to be as broad as is customary achievable with comparable dispersive external cavity designs without active electronic tuning control, indicating that the incorporation of a DMA in an external cavity does not decrease the extent of the tuning range. This in turn indicates efficient external cavity operation with strong coupling and low intracavity losses, other than the inherent losses of the DMA modulator. Additionally, as a benefit of the MEMS DMA technology, our laser contains no macro-scale moving parts, making it mechanically robust and reliable for field use. Efforts are currently underway to develop a compact monolithic version of the DMA-enabled external cavity that would entirely fit in a cube of several cubic inches, and would be able to accept multiple QCL gain chips.

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