Miniature Self-Aligned External Cavity Tunable Single Frequency Laser for THz Generation

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ABSTRACT

We report on the unique highly-configurable wavelength tuning and switching properties of a tunable external cavity laser based on multiplexed volume holographic gratings (VHGs) and a micromirror device. The ultra-compact laser has a 3 THz bandwidth and exhibits single mode operation in either single or multiple wavelengths with narrow linewidth (<7.5MHz), and a switching rate of 0.66KHz per wavelength. A prototype laser exhibited 40 mW of output power for wavelengths from 776 - 783 nm. The unique discrete-wavelength-switching features and low power consumption of this laser make it well suited as a source for continuous-wave (cw) terahertz signal generation in portable photomixing systems.

Keywords: tunable laser, terahertz, photomixing, terahertz spectroscopy

1. INTRODUCTION

THz spectroscopy is gaining a strong foothold as a critical technology for applications ranging from explosives detection to security screening and materials analysis. However, to be fully enabled in field-deployable environments such as law-enforcement, military and industrial settings, a compact, robust, low-power-consumption laser source that can be precisely tuned over a range of several nm in the near infrared is required. For portable and hand-held applications, temperature tuned DFB lasers have been used for coherent cw THz photomixing[1] since they provide smooth, mode-hop-free frequency tuning that enables high resolution THz spectroscopy in small and rugged packaging. However, DFB lasers have a limited temperature-tuning range of just a few nm, which limits the THz signal generation to less than 2 THz. It would be desirable to extend the tuning range to at least 4 THz to improve the capability to identify various unknown substances. To overcome this limitation, we propose to combine a continuously tunable DFB laser with a novel discrete tunable laser with a much larger tuning range[2]. This approach takes advantage of the continuous tuning capability of the low-cost DFB to achieve fine-frequency control, and the rapid and large-range tuning of the discrete laser to enable a wider spectrum of THz frequencies to be accessed. The construction of the discretely-tunable laser, described in detail below, also lends itself to rugged and small-sized packaging suitable for portable applications, and has inherently low power consumption.

2. METHODOLOGY

2.1 Discrete Tunable Laser Architecture

Our novel design for a self-aligned external cavity laser[2] is shown in Figure 1. The P-polarized light from the laser diode (LD) is collimated by the lens L1 and transmitted through the polarizing beamsplitter (PBS). A $\lambda/4$ plate changes the polarization to circular before the light reaches a multiplexed Volume Holographic Grating (VHG). Here a portion of the light is diffracted back towards the $\lambda/4$ plate. After passing the $\lambda/4$ the now S-polarized light is directed by the PBS towards the lens L2 and a Digital Micromirror Device (DMD) array.

The multiplexed VHG is designed to have different diffraction angles for each of the discrete diffraction wavelengths. The relation between wavelength and angle is arbitrary (unlike dispersive gratings) and is permanently set during recording of the grating. The diffraction angle for each wavelength is chosen to ensure that the individual wavelengths are focused onto separated micro-mirrors on the DMD. By switching the individual mirrors, discrete wavelengths can be selected to be reflected back into the cavity. An AR coating on the diode output facet suppresses lasing at other wavelength than the "On" wavelengths which are fed back by the external cavity.

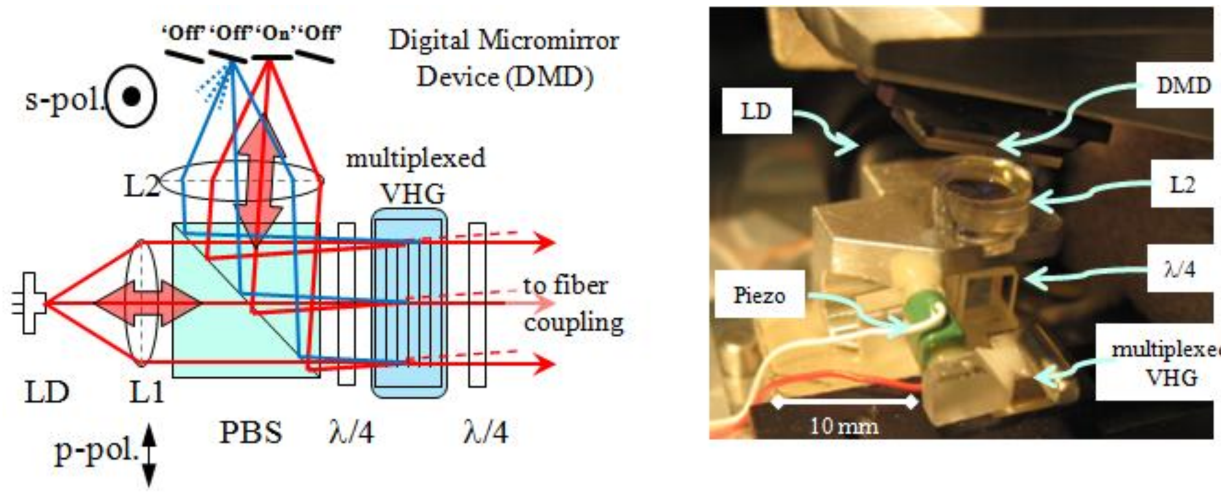

Figure 1. Schematic layout and photograph of discrete tunable external cavity laser.

Both laser diode and DMD are located in the focal plane of the lenses, making the angular tolerances of the optical components quite forgiving for the entire cavity. Since no direct access is required, the laser facet and micro mirrors can remain in hermetically sealed packages at all times.

The layout can readily be adapted to add additional wavelength tuning capabilities. By mounting the VHG on a piezoelectric actuator the external cavity length can be precisely controlled. This enables continuous wavelength tuning with MHz resolution over the tuning range corresponding to the external cavity mode spacing.

2.2 Discrete Tunable Laser Prototype

To demonstrate the capabilities of our design we choose an AR coated ridge wave guide laser diode capable of lasing between 750 and 780 nm (Eagleyard). A commercially available DLP micro mirror array from Texas Instruments was used as the DMD element. The DMD is computer controlled by a standard graphics card with a VGA connection. To maintain a stable optical path length, all components other than the DMD are temperature controlled by a thermoelectric cooler (TEC) module. The operating temperatures of the laser diode and the external cavity can be controlled with 0.01°C precision. The compact size of the optical set-up (only about $1cm^3$) enables fast response times to thermal fluctuations induced by the environment. The power consumption of the TEC when operated near ambient temperature was below 0.3 W, and the maximum drive current to the laser diode was 165 mA to achieve a free-space output power level of 42 mW. The 5 channel multiplexed VHG is produced by Ondax using proprietary photorefractive glass and recording techniques. The effective optical path length for a round trip of the external cavity is ~ 80 mm, giving a mode separation distance of about 3.8 GHz.

The output from our laser is a collimated ~ 2 mm $1/e^2$ diameter beam. The collimated beam is fiber-coupled into polarization maintaining fiber using a fiberport (Thorlabs, PAF-X-7-B) with fiber coupling efficiency of 55%, indicating excellent free space beam quality. The discrete wavelengths are chosen to achieve a continuous tuning range of more than 4 THz in combination with the DFB laser. The DFB laser wavelength λ_{DFB} varies nearly linearly with temperature T: λ_{DFB} = 784.65 nm + 0.052 nm/K (T-25°C). The mode-hop-free temperature tuning range of the DFB is limited to 10 to 45°C. Table 1 lists the chosen set of discrete wavelengths and the resulting THz frequencies expected when mixed with the temperature tuned DFB laser (Emcore Model PB1316-783). The results indicate that stable THz generation is achievable up to 4.35 THz by tuning the discrete laser across the five channels. Fine frequency resolution can be obtained by temperature-tuning of the DFB such that continuous tuning from 0.15 THz to 4.35 THz is achievable in principle with this setup. The output power of the discrete-tunable laser appeared to be limited by damage to the DMD array at high intensities above 40 mW of free-space output power, but this effect requires further investigation. The fact that the laser-to-fiber coupling could be maintained at 55% across the entire tuning range with no manual adjustments necessary is indicative of the stability of the optical design, and extensibility to more rugged packaging appears feasible.

Channel #	Discrete Wavelength	Minimum mixing frequency	Maximum mixing frequency	Laser drive current	PM fiber coupled power
--	nm	THz	THz	mA	mW
1	783.53	0.15	1.04	97	10
2	781.83	0.99	1.87	150	15
3	780.13	1.82	2.70	165	22
4	778.46	2.64	3.53	145	15
5	776.80	3.47	4.35	145	15

Table 1. Set of 5 wavelengths for the discrete tunable laser, and the resulting THz frequency range accessible by mixing with the temperature tuned DFB laser, drive current and power out of polarization-maintaining optical fiber.

2.3 Terahertz Frequency Generation Set-Up

Figure 2 shows an overview of the THz wave generation and detection set-up used in our experiments. The light from the two spectrally stable lasers operating at different wavelengths is combined via a 50/50 fiber beam splitter. The outputs from the beamsplitter are each focused onto separate photomixer elements. At the photomixer the total light intensity is fluctuating with the beating frequency of the two optical frequencies and modulates the photoconductivity of the element. On the emitter side a current biased antenna structure allows coupling of the THz waves out of the photomixer into free space. Similarly on the detector side, the incident THz wave drives a detectable current in the antenna structure. This current is coherently detected by photomixing with the same optical beat signal. The spectral signature of a device or material under test is obtained by scanning the beat frequency and recording the amplitude of the detected signal. Detection sensitivity is typically boosted by modulating the voltage bias on the emitter antenna and using lock-in techniques on the detector side for noise rejection[3]. For our experiments we use photomixers and detection circuitry from a commercially available Terahertz Spectrometer (Emcore, PB2700)[4].

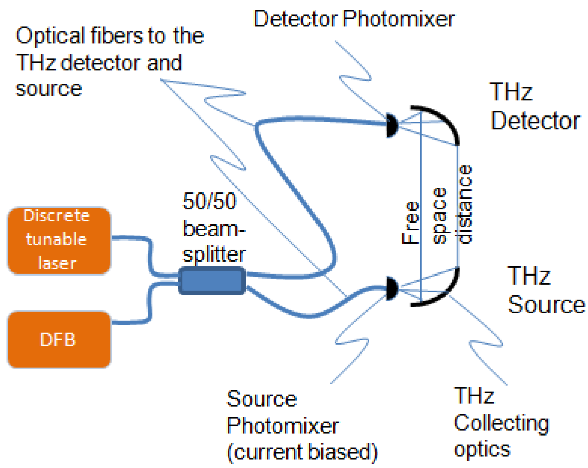

Figure 2. Schematic layout of the THz wave generation and detection set-up.

The usable maximum THz frequency is ultimately limited by the photomixers[5] since generation and detection efficiencies drop with increasing frequency. State of the art photomixing systems have been shown to cover a frequency range of up to approximately 2 to 3 THz.

3. RESULTS

3.1 Discrete Tunable Laser Performance

Free space optical output powers of up to 42 mW were measured. Accounting for the 55% coupling efficiency into polarization maintaining fiber, this amounts to up to 22 mW of optical power from the fiber. For all 5 channels at least 10 mW of optical power out of the fiber are achieved.

Figure 3 shows the lasing wavelength while the laser is cycling through all 5 channels. The laser is operated for about 5 seconds at a time before switching to the next wavelength. A wavemeter (Coherent, WaveMaster) is used to measure the lasing wavelength. The observed wavelength repeatability is better than 3 pm for the individual channels – outstanding for an open loop system.

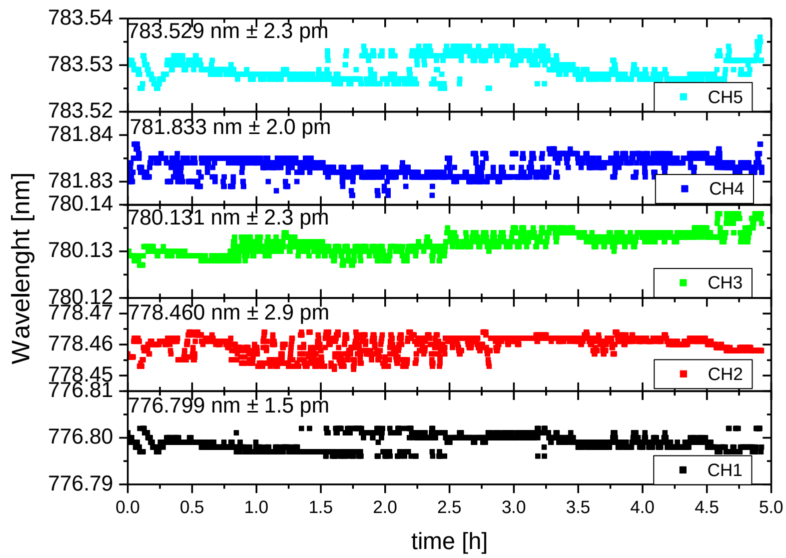

Figure 3. Wavelength switching repeatability for approximately 3600 switching events.

The switching dynamic between 2 arbitrary chosen channels is shown in Figure 4. The intensity for the individual wavelength rises and falls nearly exponentially with a time constant of 50 µs (about 185 µs for 99/1 % level). These switching times are independent of the change in wavelength and only limited by the maximum speed the micro mirrors can be moved between the 'on' and 'off' positions. No settling time after switching is required since the wavelengths are determined by the permanently fixed volume holographic gratings.

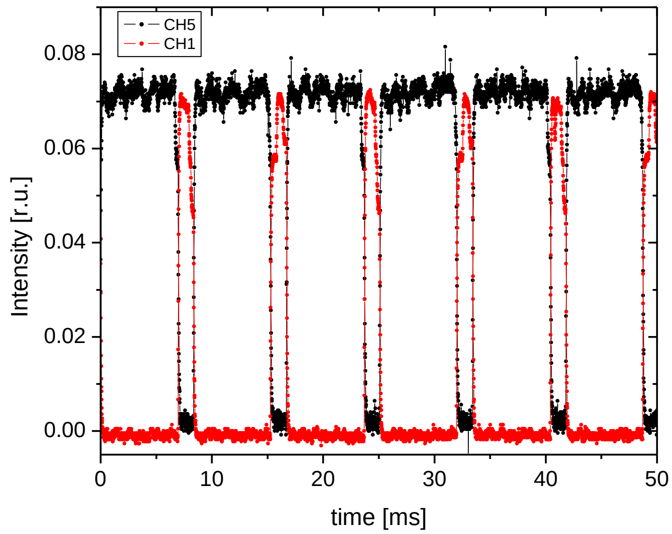

Figure 4: Fast wavelength toggling with 120 Hz and 185 μs rise and fall time.

Further fine tuning of the wavelength can be achieved by changing the external cavity length using a piezoelectric actuator. Frequency variation as a function of voltage on the piezoelectric actuator is shown in Figure 5. We measured an effective tuning coefficient of 180MHz/V (corresponding to 0.36 pm/V) with a tuning range of up to 1.8 GHz (4 pm).

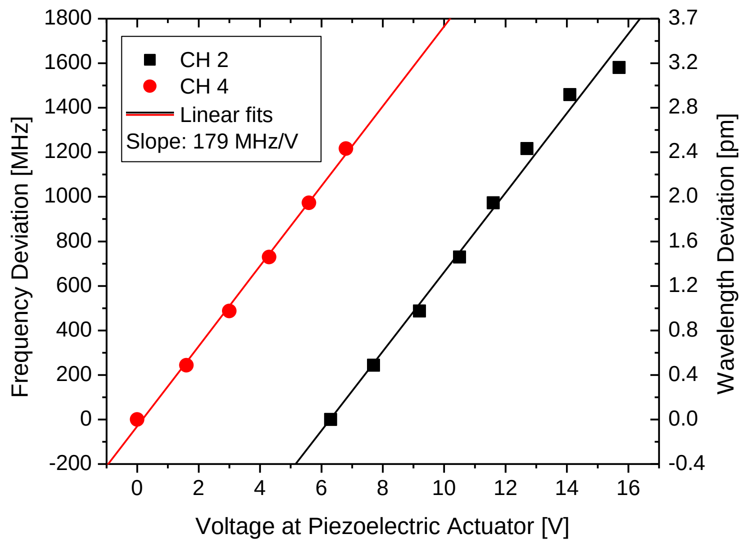

Figure 5: Individual channel fine tuning with piezoelectric actuator.

A scanning Fabry-Perot interferometer is used to investigate the spectral width for the individual channels. The results shown in Figure 6 indicate that the linewidth is below our instrument resolution (7.5 MHz). Other lasers we have built with similar external cavity configurations exhibit line widths below 1 MHz measured by self-beating techniques. Thus, we estimate that the linewidth of each wavelength of this laser is below 1 MHz.

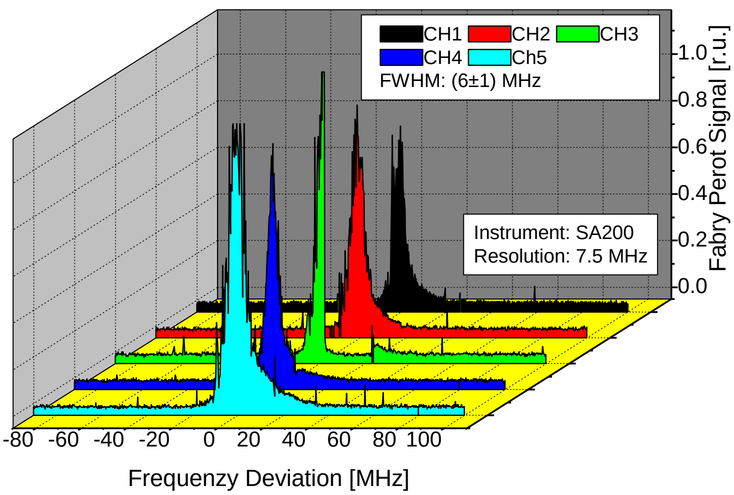

Figure 6: Linewidth measurements for individual channels.

3.2 THz Wave Spectroscopy

For the THz experiments the discrete tunable laser is set to a fixed channel and the DFB is thermally tuned from minimum to maximum difference frequency (see Table 1). Optical power from the fiber was measured to be 10, and 15mW for Channels 1 and 2, respectively. In order to achieve maximum contrast, the DFB drive current was adjusted to match the optical power of the discrete laser. Results are shown in Figure 7. For the first 2 channels, covering a frequency range of approximately 2 THz, a clear THz signal could be observed that was in line with expected levels based on the optical power levels. The increase of THz power by approximately 7 dB at 1 THz for Channel 2 compared to Channel 1 is in line with the increase of laser power from 10 mW to 15 mW (1.8 dB), since the RF detected power varies as the 4th power of the laser intensity for a coherent photomixing system. Higher optical powers and better integration of the lasers with the detection circuitry are expected to improve the dynamic range in future experiments.

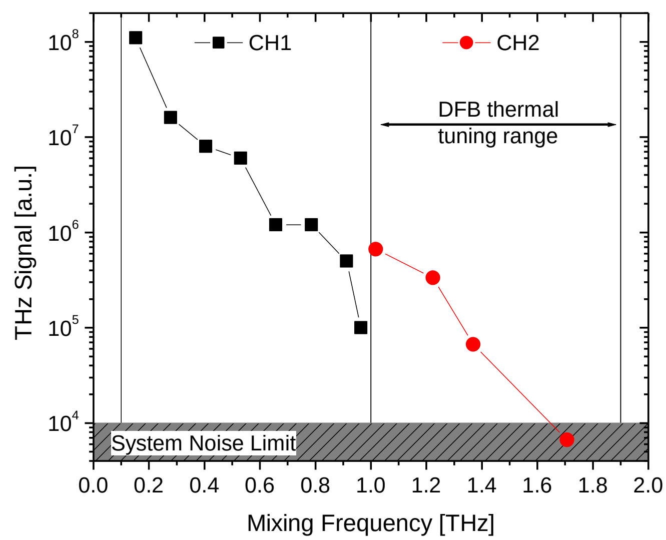

Figure 7: Detected THz signal as a function of frequency difference between DFB and discrete tunable laser.

4. SUMMARY

A compact and discretely tunable external cavity laser suitable for THz spectroscopy in portable, battery-operated applications has been demonstrated. The laser is rugged since wavelength switching is performed without mechanical moving parts. The performance of a laser with 5 switchable wavelengths spanning over 6 nm around 780nm is presented. The main features of the prototype are better than 3 pm wavelength repeatability over 5 hours, less than 7.5 MHz linewidth and up to 22 mW of optical power at the output of a polarization maintaining fiber. The tunability exhibited will support THz generation from 0.15 THz to 4.35 THz. Laser power levels were limited in this first prototype which limited the achievable THz output power and tuning range. Further refinements of the setup are expected to improve the signal-to-noise ratio and tuning range.

ACKNOWLEDGEMENTS

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