Quasi-Continuous Wavelength Tuning of Interband Cascade Lasers Based on V-coupled Cavity

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ABSTRACT

Mid-infrared semiconductor lasers have a wide range of applications in gas sensing, environmental monitoring, medical diagnosis and other fields. The V-coupled cavity laser (VCCL) approach has been successfully applied in the communication band to achieve single-mode operation with a wide tuning range because of its advantages of no grating, compact structure and simple wavelength control. In this paper, the concept of V-coupled cavity is introduced to the interband cascaded lasers, and a monolithically integrated mid-infrared widely tunable single-mode laser is developed. In addition, we experimentally demonstrated a simple and general algorithm for wavelength tuning controlled by two electrodes synchronously, and realized quasi-continuous tuning of single-mode wavelength in mid-infrared interband cascade laser based on the V-coupled cavity configuration for the first time.

In the tuning process, the injection current of the short cavity remains unchanged, and the stepped increase of the long cavity current is equivalent to the realization of discrete tuning with the channel spacing of 1.1 nm determined by the short cavity. With the increase of the injection current of the coupler electrode while fixing the long cavity current, the thermo-optic effect caused by the coupler current will cause the refractive index of the two FP cavities to change together, thus realizing the fine tuning of the laser wavelength. A total tuning range of 53.2 nm has been achieved, from 2.8244 μm to 2.8776 μm, with the temperature adjusted from 110K to 120K.

Keywords: Tunable laser, single-mode laser, interband cascade laser

1. INTRODUCTION

Widely tunable single-mode mid-infrared lasers are ideal for many applications such as gas detection and biomedical fields[1]. Many tunable semiconductor lasers have been developed over the years. For example, the sampled grating distributed Bragg reflection (SG-DBR) laser uses two groups of sampled gratings to generate the Vernier effect of two comb spectra with slightly different free spectral ranges (FSRs) to achieve the wide tuning range[2]. In 1996, a super structured grating distributed Bragg reflection (SSG-DBR) laser was proposed and demonstrated to achieve a quasi-continuous tuning of 34 nm[3]. However, these tuning schemes need to tune the injection current of three electrodes synchronously. Therefore, a complex tuning algorithm is needed. For mid-infrared applications, single-mode operation has been realized by using distributed feedback (DFB) lasers[4-6]. However, the tuning range of DFB laser is usually limited to a few nanometers, and the grating with precise period needs to be made. The external cavity lasers can also be used to achieve single-mode operation with a wide tuning range, but the mechanical components make the system bulky and expensive.

In recent years, the concept of compact V-coupled cavity laser (VCCL) with half-wave coupler has been proposed for widely tunable single-mode operation, and has been verified in the near-infrared communication band[7,8]. The V-coupled cavity tunable laser does not involve any grating or ring resonator, and it does not need any epitaxial regrowth. The fabrication process is similar to that of a simple Fabry Perot laser. In this paper, we combine the interband cascade lasers (ICLs)[9-13] with a half-wave V-coupled cavity structure to realize a widely tunable single-mode mid-infrared semiconductor lasers without complex gratings. In addition, a simple dual electrode synchronous wavelength tuning algorithm is proposed and demonstrated experimentally. The single-mode quasi-continuous tuning of the interband cascade laser is realized based on a V-coupled cavity for the first time.

2. DEVICE DESIGN

2.1 Antimonide-based interband cascade laser structure

Type II interband cascade laser (ICL)[9] is relatively new type of semiconductor lasers, in which each injected electron can generate multiple photons within the same optical cavity for high quantum efficiency and differential gain. Since the initial proposal in 1994[9], ICLs have been developed to cover a wide range of mid-infrared spectrum (e.g. 2.7 to 11 µm) with excellent device performance[10-13]. For example, ICLs achieved cw operation at temperatures up to 115°C with low threshold-current densities (*e.g.* 100 A/cm^2 at 300 K), low power consumption (<0.1 W at threshold at 300 K), cw output power exceeding 500 mW at room temperature and room temperature cw operation with lasing wavelengths from 2.7 to beyond 6 µm[13], as well as successful operation on Mars for detection of CH_4[14].

To demonstrate the widely tunable single-mode laser in the mid-IR spectrum based on the half-wave V-coupled cavity configuration, an ICL wafer is chosen for an initial proof of the concept, as opposed to achieving optimized device performances. This ICL wafer is based on InAs/GaSb/AlSb polytype heterostructure material system[15] grown on a GaSb substrate[10]. The ICL structure comprises 12 interband cascade stages sandwiched by two InAs/AlSb superlattice cladding layers[10]. Each cascade stage contains an active region of an AlSb/InAs/GaInSb/InAs/AlSb W-type quantum well[16-17], a hole injector and an electron injector as shown in Fig. 1. This ICL structure has previously been processed using wet etching into 20-µm-wide ridge laser devices that could lase in pulsed mode at temperatures up to 325K and at an emission wavelength near 3.19 µm. In continuous wave (cw) operation, these wet etched ICL devices could lase at temperatures up to 208 K with a threshold current density (voltage) ranging from ~28 A/cm^2 (5.89 V) at 80 K to 517 A/cm^2 (6.28 V) at 208 K, covering wavelength range from ~2.86 (80 K) to 3.065 µm (208K). Although the device performance of ICLs made from this wafer is far below the state-of-the-art, it is good enough for the initial demonstration of the half-wave VCCL approach.

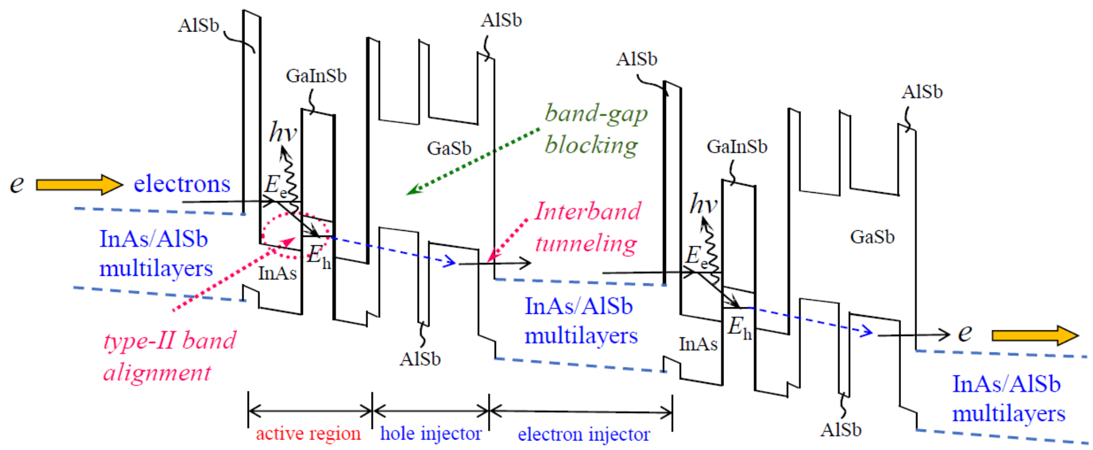

Figure 1. Schematic band diagram of interband cascade laser structure.

2.2 Principle of the V-coupled cavity laser

In order to achieve a single-mode operation with a wide tuning range, the V-coupled cavity configuration is implemented into the ICL structure. A monolithically integrated half-wave VCCL is shown in Fig. 2, in which two Fabry-Perot (FP) cavities of different lengths are connected through the half-wave coupler. The detailed working principle of VCCL is described in reference 7. The V-coupled cavity laser consists of two FP cavities with a small cavity length difference and a half-wave coupler. The two FP cavities are coupled at the coupler and are defined by etched facets. The whole device has the shape of "V". The single longitudinal mode output can be obtained by the mode selection of the coupler, and the laser can be tuned in a wide range through the Vernier effect between two FP cavities of slightly different optical path lengths. By scanning the size parameters of the half-wave coupler, the coupling coefficient and phase are optimized to obtain high mode selectivity. High reflection coating is used on the end facet of the half-wave coupler to further reduce the loss. Three electrodes were deposited for current injection, including coupler electrode, long cavity electrode and short cavity electrode. The coupler electrode covers 60% of the FP cavity while covering the coupler, which is mainly used to provide the gain. The long cavity electrode is used to select the wavelength channel by changing current injected into the long cavity. The short cavity electrode is used to provide fixed gain and auxiliary tuning. In this design, the length of the short cavity is 1000 microns, and the long cavity is 5% longer. The fabrication of the IC-VCCL is described in reference 18.

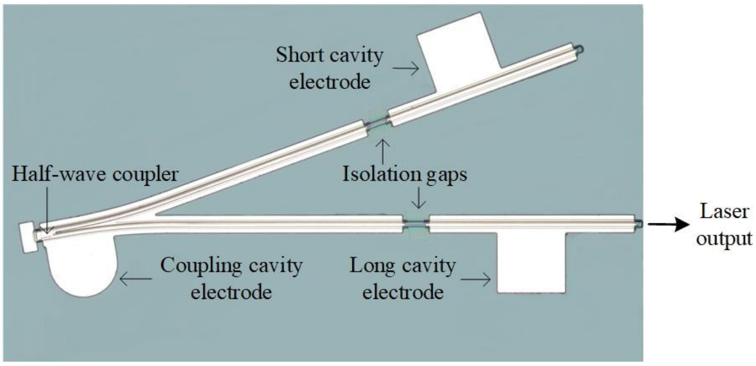

Figure 2. Schematic diagram of the V-coupled-cavity laser.

3. TUNING ALGORITHM

As shown in Fig. 3, in order to achieve quasi-continuous tuning in a V-coupled cavity laser, the resonant frequency combs of the two cavities should be tuned synchronously at the same tuning speed to avoid mode hopping. We only need to tune the wavelength combs of two cavities synchronously by one channel spacing before jumping to the set current of the next channel. At this time, the next resonant peak of the long cavity coincides with the next resonant peak of the short cavity, we can thus realize quasi-continuous tuning in a certain wavelength range.

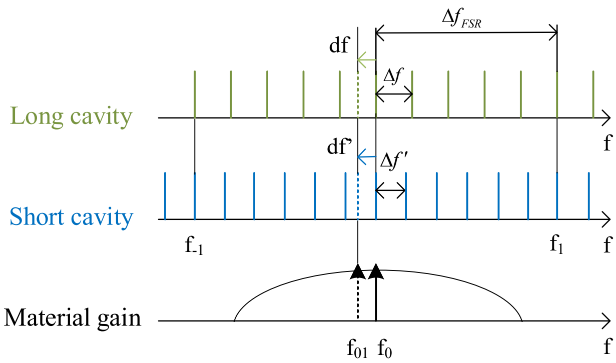

Figure 3. Schematic diagram of the synchronous frequency comb shift.

According to Fig. 2, the coupler electrode covers a part of the two FP cavities, and its proportion to the total cavity length is the same for the two cavities. Theoretically, when the injection current of the coupler electrode is increased, the thermo-optic effect caused by the injection current will cause the refractive index of the two FP cavities to change together, so as to realize the fine tuning of the laser wavelength. Tuning a single electrode on the coupler can achieve wavelength fine tuning. In order to achieve a wide range of quasi-continuous tuning, it is also necessary to tune the long cavity current when the wavelength fine tuning reaches a channel spacing, so that the alignment mode of two cavity frequency comb is switched to the next channel. The waveform of the driving current is shown in Figure 4. The injection current of the short cavity remains unchanged during the fine tuning process. The switch of discrete tuning with 1.1 nm interval is realized by increasing the long cavity current step by step. The current injected into the coupler has a sawtooth waveform, which can realize the wavelength fine tuning within each channel.

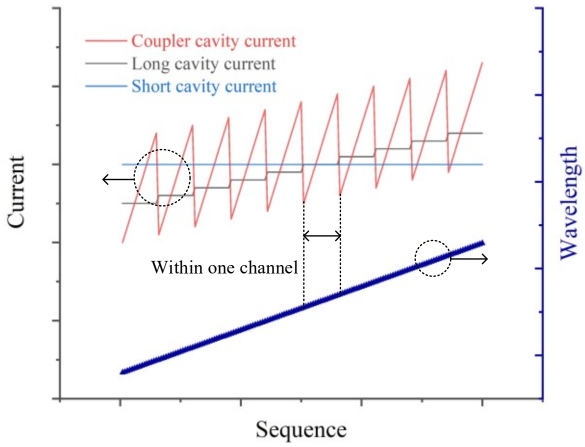

Figure 4. Waveforms of the driving currents and the quasi-continuous tuning of the laser wavelength.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Test system

Compared with the near infrared InP based laser, the measurement of antimonide-based mid-infrared laser is more challenging due to the lack of standard tools. Frequently, a mid-infrared laser needs to be tested at low temperatures (*e.g.* 78 K) with liquid nitrogen cooled equipment. In addition to the high requirements for the test system, the packaging process of the laser chip is also more complex. On the other hand, the laser test in near-infrared band only needs fiber coupling with standard interfaces to the power meter and spectrometer , and has been automated. However, the measurement of a mid-infrared emitter often needs careful alignment of free-space optical components, so the complexity of the test is increased with a high cost and a low efficiency.

In this experiment, a scientific research grade liquid nitrogen cooled cryostat from CYRO company and a temperature controller from Lake Shore Cryotronics Inc. were used. It can control two temperature sensors and one heater to adjust the temperature from 77 to 325 K. There are four windows below the nitrogen cooled cryostat for laser output, and a CaF_2 window is generally used for mid-infrared spectrum (2-7 μm with ~ 10% transmission loss). A source meter from Keithley was used, which can monitor the voltage of the laser chip while injecting current to the laser device. The laser output power was measured by Thorlabs 180C MCT power meter. The power meter with integrating sphere has a large receiving area and can be directly placed outside the window to receive the laser beam without using an external optical lens. The emission spectra were acquired by a Fourier transform IR (FTIR) spectrometer from Bruker Vertex 70 with a spectral resolution of 0.3 cm^{-1}.

4.2 Electrical and optical characteristics of the V-coupled-cavity laser

Fig. 5 shows the bias voltage and output power curves of V-coupled cavity laser at different temperatures. Since the coupler section mainly provides the gain, the output power varies with the current through the coupler electrode in the experiment. The waveguide width of the laser is 8μm. The short cavity length is 1000 μm, and the long cavity is 5% longer. It can be seen from the figure that the threshold current of the VCCL increases with increasing temperature. The laser output power was detected from one facet of the long cavity and can be higher than 1mW. It can be seen that the linearity of power-current curve in the figure is not good. This is mainly due to the fact that the quantum efficiency decreases with increasing current due to thermal effect. Moreover, mode hopping may occur when the coupler current varies, which makes the output power to have some fluctuation.

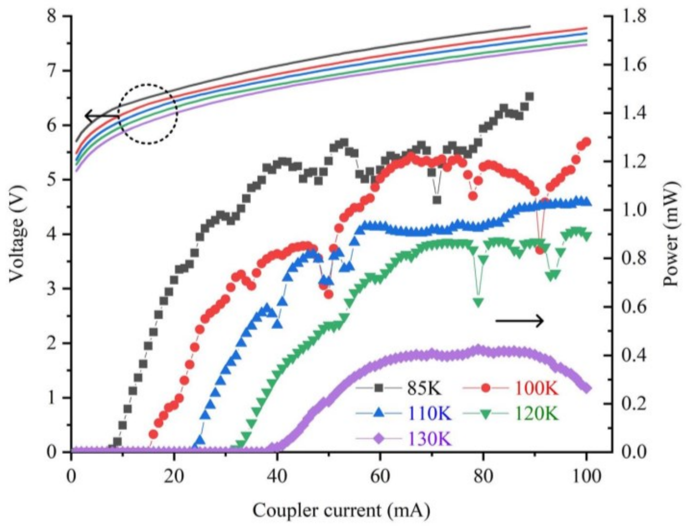

Figure 5. Output power and operating voltage vs. the coupler current for a mid-infrared interband cascade VCCL at different temperatures.

4.3 Spectral characteristics of the V-coupled-cavity laser

Fourier transform infrared spectrometer (FTIR) is the most commonly used spectrometer in mid infrared, which is based on Michelson interferometer system. The two arms of Michelson interference have a moving mirror and a fixed mirror respectively, through which with interference an optical beam reaches the detector. The laser interference spectrum with different optical path difference (i.e. different phase) is obtained by modulating the moving mirror, which is equivalent to Fourier transform of the optical spectrum. The interference spectrum contains the information of laser wavelength and intensity, and can be converted into the optical spectrum by inverse Fourier transform.

Fig. 6 shows the quasi-continuous tuning spectra of the interband cascade VCCL obtained by the FTIR spectrometer Bruker vertex 70. A total of 47 channels with a quasi-continuous tuning range of 53.2 nm were achieved by adjusting the currents on the coupler and the long cavity electrode. The wavelength of the laser was tuned from 2.8244 μm to 2.8776 μm. As predicted by the Vernier principle, when only the injection current of the long cavity electrode increases, the laser wavelength will be tuned to a longer wavelength. The channel spacing is about 1.1 nm, which varies slightly with the increase of temperature. When the long cavity current is fixed, the laser wavelength is tuned in a small range within the channel spacing with the coupler electrode current. As shown in Fig. 7, which provides the expanded view of the fine tuning, the wavelength is tuned within a channel from 2.8480 μm to 2.8491 μm by increasing the coupler current.

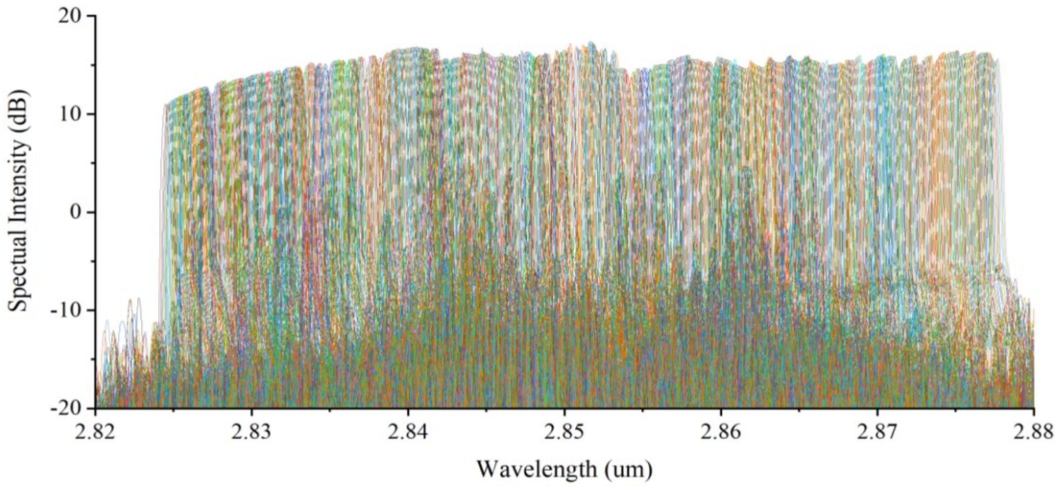

Figure 6. Overlapped spectra of the quasi-continuously tuned ICL based on V-coupled cavity configuration.

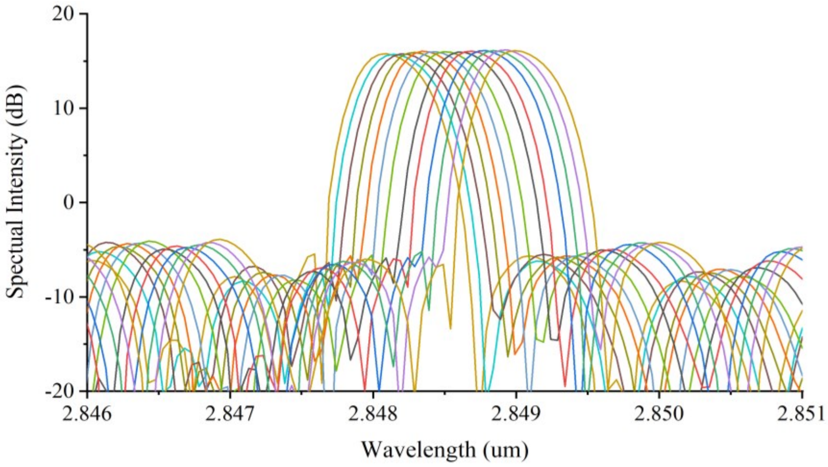

Figure 7. Expanded view of the fine tuning within a channel.

The relationship between the specific wavelength and the current is shown in Fig. 8(a), which can be divided into three parts. The details of the applied currents, temperature and the resulting wavelength ranges are shown in Table 1. The first and second parts are obtained by tuning the long-cavity current with the short-cavity current fixed at two different values and the temperature fixed at 110 K. The third part is tuning at 120 K. At 110 K, the V-coupled cavity laser can be tuned by 28.9 nm, from 2.8244 to 2.8533 nm. By changing the temperature to 120 K, the lasing wavelength was extended to 2.8776 μm with a total tuning range of 53.2 nm. Fig. 8(b) shows a single-mode spectrum of the device at 110 K with a side-mode suppression ratio (SMSR) of 30 dB. The injection currents of the coupler electrode, long-cavity electrode, and short-cavity electrode are 49 mA, 10.8 mA, 14.5 mA, respectively.

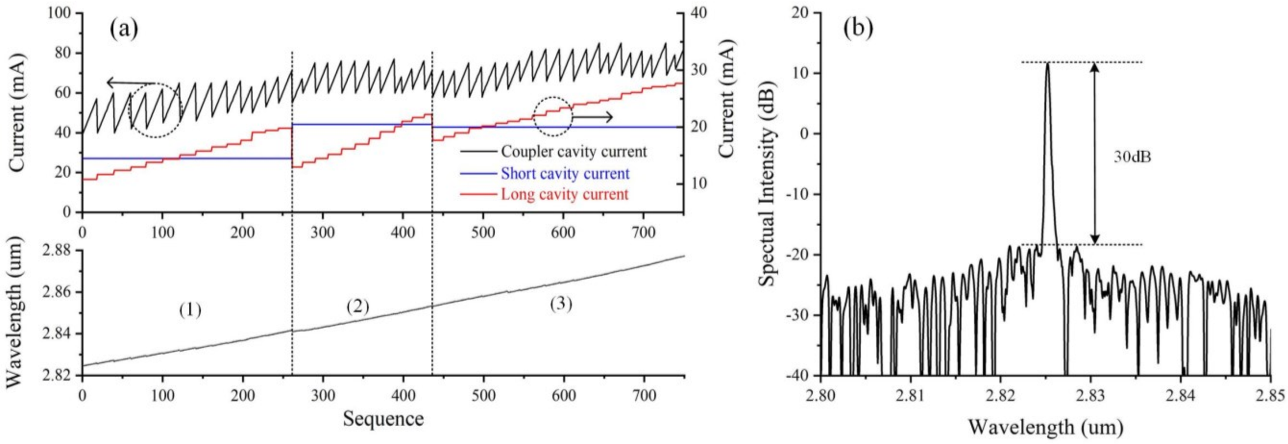

Figure 8. (a) Wavelength variation with injection current. (b) The single-mode spectrum with a SMSR of 30 dB.

Table 1. Three part details in Figure 7 (a).

Item	Temperature/K	Coupler electrode current/mA	Long cavity current/mA	Short cavity current/mA	Wavelength/nm
(1)	110	40-71	10.8-19.8	14.5	2.8244-2.8416
(2)	110	55-71	13.0-22.2	20.0	2.8401-2.8533
(3)	120	58-87	17.7-27.7	20.5	2.8532-2.8776

5. CONCLUSION

In conclusion, we have demonstrated the first widely tunable single-mode mid-infrared ICL based on monolithically integrated half-wave V-coupled cavity structure. In a grating based single-mode laser, a large temperature change may lead to the mismatch between the laser wavelength determined by the grating and the gain spectrum of the material, thus limiting the working conditions of the laser. However, the VCCL can use the temperature change to increase the wavelength tuning range. In our preliminary demonstration, the quasi-continuous wavelength tuning range reaches 28.9 nm at a fixed temperature. When the temperature is adjusted, the wavelength tuning range can be expanded to 53.2 nm. Single-mode emission with SMSR up to 30 dB has been achieved. In the future, the performance of the device can be further improved by optimizing the coupler design and fabrication process with more accurate waveguide parameters (or using a state-of-the-art ICL wafer). In addition, the loss of the laser waveguide made in this experiment is larger than that of the previous experiments. It is expected that the dry etching process can be significantly improved to reduce the waveguide loss and end reflection loss, thus allowing higher output powers and higher slope efficiencies of the ICL. Through the development of electroplating process and optimization of the laser packaging, the heat dissipation of laser can be improved to obtain higher working temperature and wider tuning range. The advantages of wide tunability and simple fabrication should make the VCCL-based single-mode ICLs very promising for many mid-IR applications.

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