

Mid-infrared Interband Cascade lasers for free-space laser communication

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ABSTRACT

We have fabricated high-speed Interband Cascade lasers and provided the first experimental evidence that these devices can be directly modulated at a frequency of 3.2 GHz and above.

Keywords: semiconductor lasers, infrared sources

1. INTRODUCTION

Optical sources operating in the atmospheric window of 3-5 microns are of particular interest for the development of free space optical communication link. It is much more advantageous to operate the free space optical communication link at wavelengths longer than the telecom wavelength of 1.5 μ m. Rayleigh and Mie scattering¹ as well as the scintillation² are much smaller for wavelengths in the 3-5 μ m band than for the 1.5 μ m wavelength. Therefore, the transmission loss of an optical link operating in the 3-5 μ m band would be significantly reduced compared to the loss of the optical link at 1.5 μ m. In addition, the combined spectral radiance of the main sources of background radiation in atmosphere (Sun, Earth, Moon, city lights, etc.) has a pronounced minimum around 3.5 μ m (Fig. 1), and thus the background noise will have a minimum as well.³ However, the realization of optical communications at the longer wavelength has encountered significant difficulties due to lack of adequate optical sources and detectors operating in the desirable wavelength regions.

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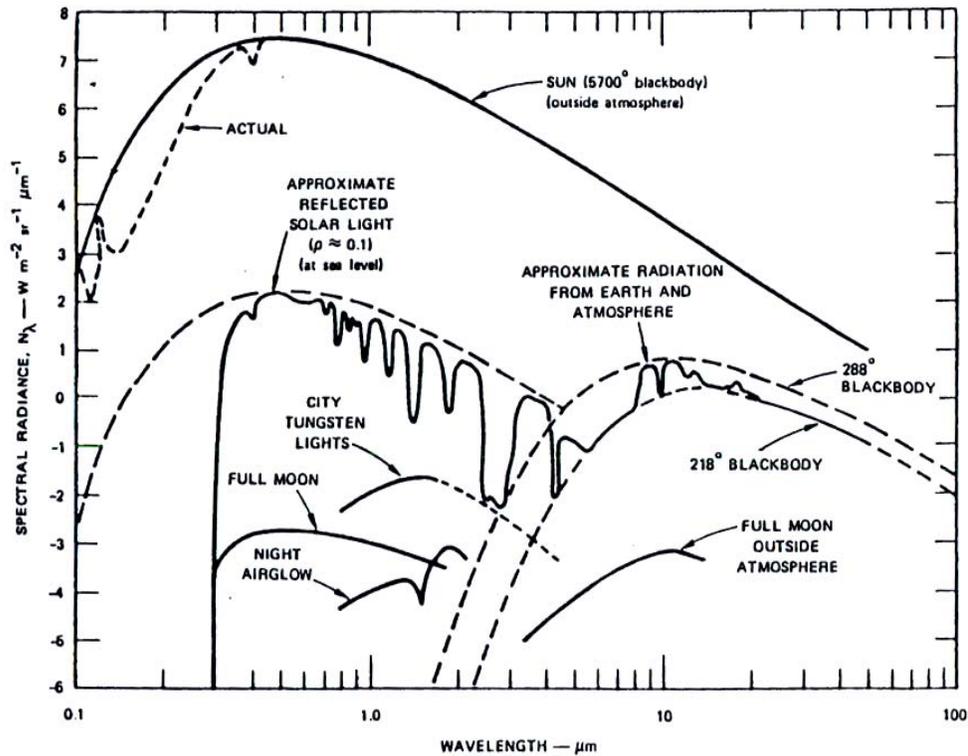


Fig. 1. Spectral Radiance of Sun and Earth.

Interband Cascade (IC) lasers⁴ are novel semiconductor lasers that have a great potential for the realization of high power, room temperature optical sources in the 3-5 μm wavelength region. IC lasers take advantage of the broken band-gap alignment in Sb-based type-II quantum wells to reuse injected electrons in cascade stages for photon generation with high quantum efficiency (Fig. 2). Significant progress has been recently achieved in the development of IC lasers, such as the demonstration of high (1 Watt) cw output power operation⁵ and high temperature operation.^{6,7} Yet, despite these developments, there is a very limited knowledge of how fast IC lasers can be modulated and no experimental work, until this one, has done on high-speed direct modulation of IC lasers. The modulation speed of IC lasers, similar to diode lasers, is related to the so-called relaxation frequency determined by photon lifetime in the cavity, differential gain and photon density. However, the special feature of IC lasers is the high differential gain, proportional to the number of cascade stages, which may lead to higher modulation bandwidth. Moreover, the study of

high speed properties of IC lasers can provide important insight into the influence of cascades on the transient laser behavior that may help to understand better the mode-locking and instabilities in Quantum Cascade lasers.^{8,9}

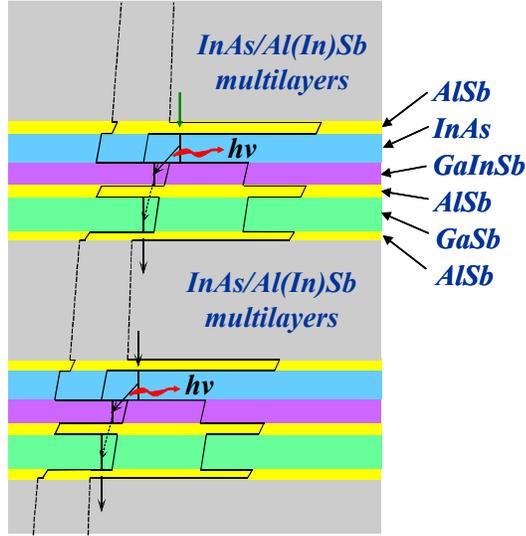


Fig. 2. Schematic band diagram of IC laser

The indirect measurement of IC laser bandwidth has been recently performed utilizing the high-speed Stark tuning of laser wavelength at frequencies up to about 1GHz.¹⁰ In this work, we developed the high-speed Interband Cascade (IC) lasers operating at wavelength $\lambda = 3.0 \mu\text{m}$ and performed the first direct measurement of their modulation bandwidth using a unique, high speed Quantum Well Infrared Photodetector.¹¹ The developed laser had modulation bandwidth exceeding 3 GHz, which opens a pathway for their use as transmitters in free space optical communication links in the mid-IR.

2. DEVICE DESIGN AND FABRICATION

Modulation bandwidth of previously demonstrated IC lasers was limited due to the parasitic effects in both laser chip and package. In particular, bypass capacitance, which is the main contributor to the chip parasitics, serves as high frequency short between the top and the bottom laser contacts and prevents fast modulation of the laser. In this work we realized high-speed IC laser operation by modifying the laser layout to reduce parasitic capacitance and by optimizing the laser

package to enable low-loss transmission of the RF modulation signal. We reduced parasitics by developing a thick insulating SiO₂ coating and by developing the laser layout with miniaturized bonding pads.

We evaluated the high speed performance of our standard structures reported previously.⁶ These lasers have 12 cascade stages grown in a solid source Veeco Applied-EPI Gen-III molecular beam epitaxy (MBE) system on undoped p-type GaSb substrates. After the epitaxial growths, parts of the wafer were processed into broad-area mesa stripe (100 or 150- μm -wide) lasers and narrow mesa stripes with a width of 10- μm . In the latter devices, a thick ($>2\ \mu\text{m}$) SiO₂ insulating coating has been deposited on the side of the laser ridge to reduce the parasitic capacitance between the top laser contact and conductive substrate. Two-mm long lasers were mounted onto an oxygen free copper holder and wire bonded to 50 Ω RF microstrip line. Lasers were mounted on the temperature-controlled cold finger of an optical cryostat that was modified to enable high speed measurement up to 18 GHz.

3. TESTS AND RESULTS:

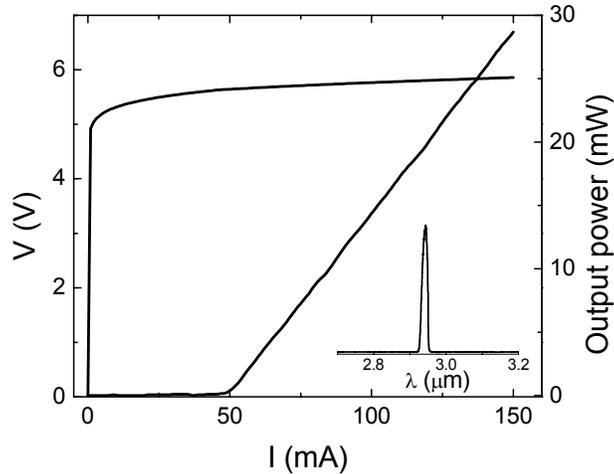


Fig. 3 Light-Current-Voltage characteristics of IC laser operating at $T=77\text{K}$. Insert: Emission spectrum of IC lasers

Figure 3 shows the Light-Current-Voltage (L-I-V) and Spectral characteristics of a broad-area IC laser used in this work. High speed measurements of IC laser were performed using set-up shown in Fig. 4. High speed modulation was achieved by driving the laser with an RF signal from a low-phase-noise signal generator. A bias tee was inserted at the input connector of the cryostat to

combine the RF modulation and laser dc bias current. The laser emission was collected by a ZnSe lens and a second lens is used to focus laser light on the liquid nitrogen cooled, high-speed Quantum Well Infrared Photodetector (QWIP). The high frequency photocurrent signal was measured with the fast QWIP (bandwidth > 15 GHz) followed by a high speed amplifier and an electrical spectrum analyzer after the bias tee.

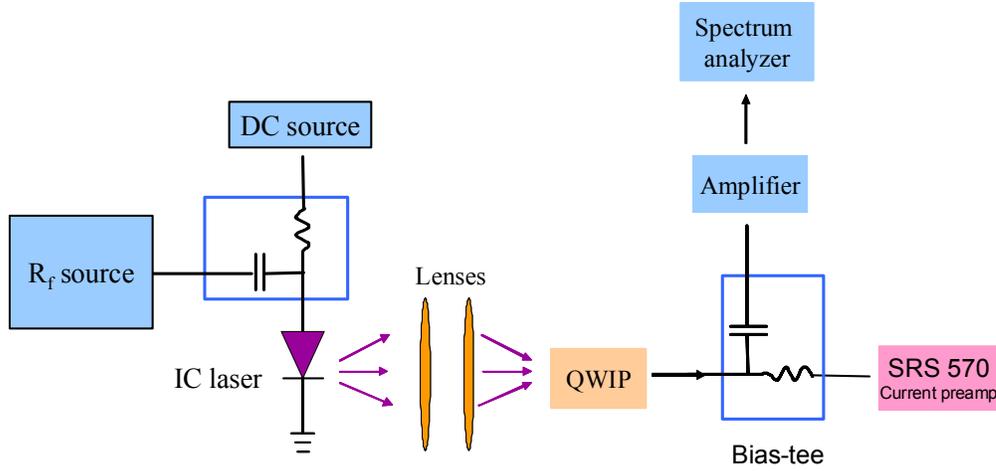


Fig. 4 Schematic of experimental set-up for measurement of high-speed response of IC lasers.

Figure 5 shows the RF spectrum of a modulated IC laser. The laser operated at $T=77$ K under applied dc bias of $I = 130$ mA and power of RF signal $P_{RF} = 10$ dBm on top of laser bias. The modulation of the laser optical signal at the frequency of 2 GHz is clearly evident from this graph. Next, we swept the frequency of RF modulation across 0.1-3.2 GHz interval (limited by RF generator bandwidth) while measuring the amplitude of transmitted RF signal as shown in Fig. 6 for different values of dc bias current (thus photon density). The high speed response of the IC laser has been calculated from the measured amplitude of RF signal by taking into account the gain frequency dependence of RF amplifier and transmission characteristics of RF components used in these experiments. As shown in Fig. 6, the differences of modulation responses between three dc bias current levels (i.e. photon density levels) was small and no high frequency roll-off was observed out to 3.2 GHz. Also, the resonant peak due to the relaxation oscillation in interband lasers was not seen in Fig. 6, implying that the relaxation oscillation frequency is higher than 3.2 GHz. These demonstrate the modulation bandwidth of IC lasers exceeds 3.2 GHz.

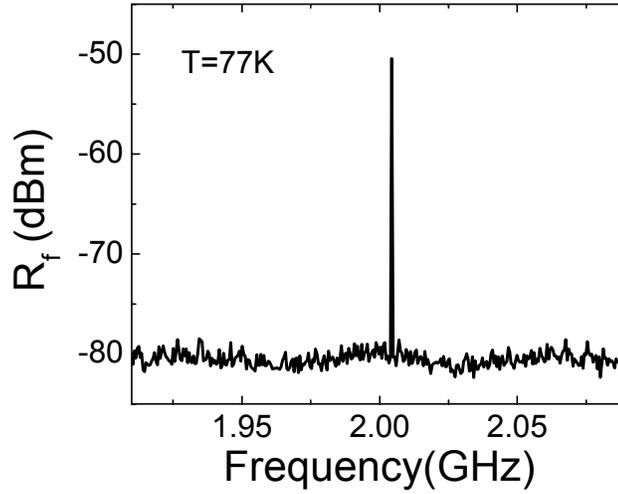


Fig. 5 Rf spectrum of modulated IC laser. The signal amplitude is shown as measured by the spectrum analyzer and is not normalized by detector quantum efficiency, analog signal chain losses, etc.

In conclusion, we have fabricated and provided the first experimental evidence that IC lasers can be directly modulated at a frequency of 3.2 GHz and above. This work has demonstrated suitability of IC lasers as a mid-IR light source for multi-GHz free space optical communications links.

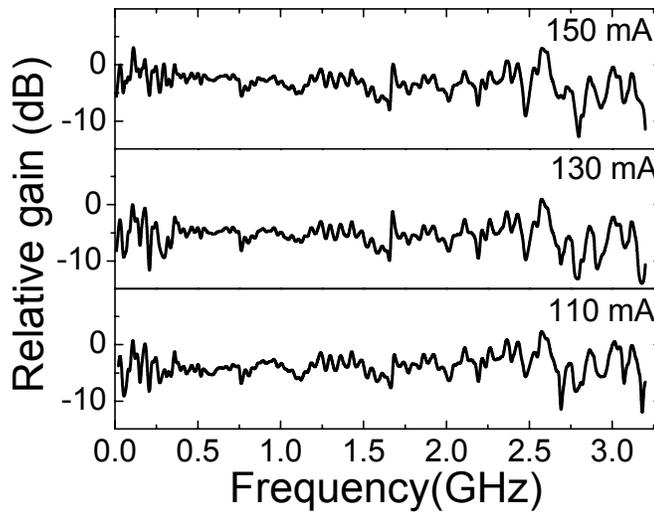


Fig. 6 High-speed response of IC laser measured with QWIP for various bias currents. The gain is relative to the signal at 100 MHz.

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