Tunable terahertz beat note generation based on a monolithic photonic integrated circuit

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Tunable terahertz waves are important in applications such as spectroscopy and imaging. They can be generated by beating two single frequency lasers on a photoconductive antenna. The tunable terahertz beat note can be realized on a monolithic photonic integrated circuit by optical heterodyning of two on-chip tunable lasers. In this paper, we have experimentally observed beat note generation from 750 GHz to 963 GHz on our first PIC. We optimized the design on our second PIC, to achieve optical power of the beat note above 20 mW. Lab characterization of the device to get the full tuning map is ongoing.

1. Introduction

Terahertz (THz) waves are electromagnetic waves within the frequency range from 0.1 to 10 THz. Since there are neither efficient emitters nor detectors in this frequency range, the THz portion of electromagnetic spectrum is also known as the "THz gap". Because of the unique nature of THz waves, they have broad applications, such as THz imaging of biological tissues based on low photon energy of THz waves, THz spectroscopy for explosives and illegal drugs detection based on their distinctive THz spectra [1].

There are three main ways to create THz sources. The first way is based on quantum cascade lasers, their lasing frequencies are however limited to the higher THz range and cannot be tuned continuously [2]. The second way uses sub-picosecond pulsed lasers illuminating on nonlinear materials or photoconductive antennas (PCA) to generate pulsed THz sources [3]. The third way is by optical heterodyning of two tunable lasers with slightly wavelength difference to generate continuously tunable THz beat notes, and then illuminating on PCAs to emit continuous THz waves [4]. Since the conversion efficiency of PCAs is around 3%, the commercially available PCAs require at least 20 mW power from the optical sources [5]. In addition, these systems for THz generation are normally bulky, which limit the applications that requiring hand-held or mobile THz devices.

Photonic integration technology allows all components for a THz system based on optical heterodyning to be realized on a single photonic integrated circuit (PIC), which provides an efficient and reliable solution for THz beat note generation in terms of size, weight and power consumption [6]. In this paper, we will present the devices that we have designed for tunable THz beat note generation integrated on a monolithic PIC, and the relevant results we have achieved from lab characterization.

2. Device design and characterization

In this paper, we chose optical heterodyning of two on-chip Distributed Bragg reflector (DBR) lasers for tunable THz beat note generation. The frequency of the THz beat note equals the frequency difference of these two DBR lasers. If we want the center frequency of the THz beat note to be around 1 THz, the center wavelength difference of these two

DBR lasers should be around 8 nm. A three-section DBR laser with 750 µm cavity length in SMART Photonics foundry was found to have a continuous wavelength tuning range of about 1.4 nm with a side mode suppression ratio above 40 dB, by tuning current injection to both DBR gratings and gain section [7]. So, beating two such lasers allows for the realization of a THz source with a tuning range of approximately 350 GHz.

2.1 The first PIC design and lab characterization

Since we chose the fabrication foundry SMART Photonics, we could use the above information to implement our first PIC design for THz beat note generation. We chose optical heterodyning of two DBR lasers that are combined in a single device on a PIC. A series of these devices was designed by combinations of two DBR lasers in one device with varying wavelength differences, to study THz beat note generation over a wide frequency range from 100 MHz to 1.25 THz.

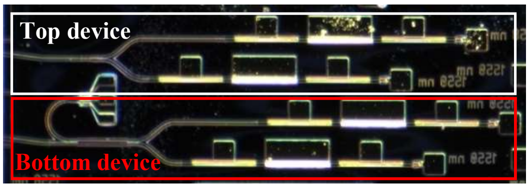
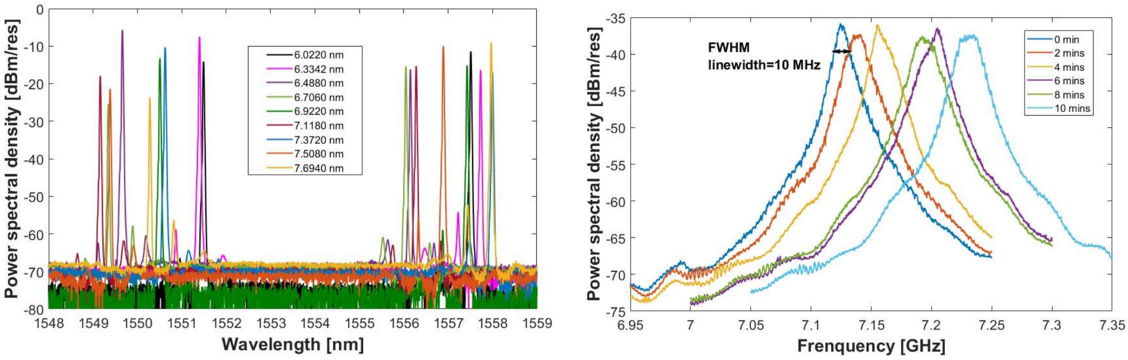


Figure 1. Microscope picture of two devices from the first PIC. Top device: Two-combined DBR laser with Bragg wavelengths of 1550 and 1558 nm respectively, Bottom device: Two-combined DBR laser with the same Bragg wavelength of 1550 nm, and one of the output ports connecting with a RF photodiode.

In this section, we will focus on two main devices on this PIC, shown in Figure 1. In the top device, the output of two DBR lasers with Bragg wavelengths of the DBR gratings at 1550 nm and 1558 nm respectively are combined into one waveguide using a 2×1 multi-mode interferometer (MMI). Moreover, a photodiode is connected to the rear DBR grating of each laser. This photodiode not only allows for monitoring of the power but also absorbs any light coming out from the rear grating and prevents the feedback to the laser cavity. We tuned the wavelengths of these two lasers to generate the beat note and measured the output power using a power meter and the optical spectra using an optical spectrum analyzer with 20 pm resolution. The measurement result is presented in Figure 2(a). The beat note frequency range we have achieved from this device is from 750 GHz to 963 GHz.



(a) (b)

Figure 2. (a) Optical spectra of THz beat notes measured from the top device in Figure 1. The wavelength separation of these two laser peaks is from 6.02 to 7.69 nm. (b) Microwave signal at frequency of 7.13 GHz by using on-chip RF photodiode measured from the bottom device in Figure 1.

The second device on this PIC is the bottom device shown also in Figure 1. It combines two DBR lasers with the same Bragg wavelength of 1550 nm together via a 2×2 MMI, which has one output port connecting with an on-chip RF photodiode. The lengths of the DBR gratings and SOAs are the same as in the top device. We could investigate the linewidth and stability of the emitted microwave signal directly by using the on-chip RF photodiode. We have measured the tunable microwave signal generation within the RF photodiode bandwidth of 18 GHz [8]. The results are shown in Figure 2(b), which indicate that the FWHM linewidth is 10 MHz at a microwave frequency of 7.13 GHz, with a drift of 100 MHz in frequency within 10 minutes.

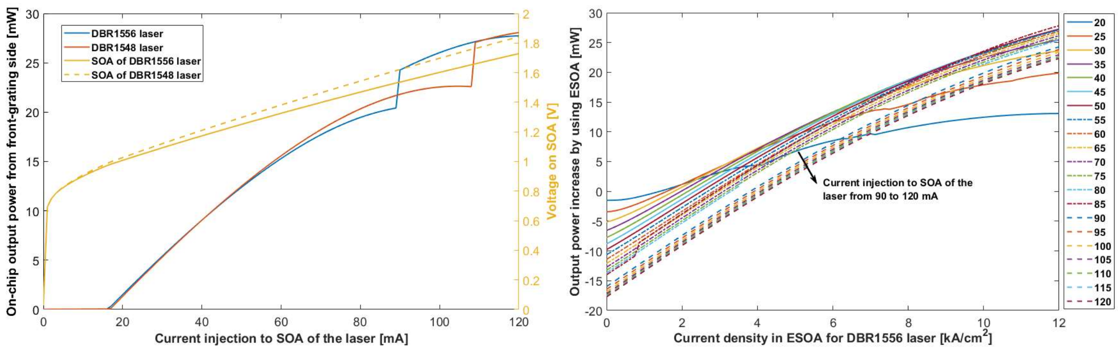
2.2 The second PIC design and ongoing lab characterization

We confirmed that it is possible to use optical heterodyning of two DBR lasers to generate terahertz beat note based on a monolithic PIC based on previous results. However, the optical power of the beat note from our first PIC was too low to meet the minimum power requirement for a commercial PCA. At this stage, we have two options to boost the power. Firstly, we could use either an Erbium-Doped Fiber Amplifier or a fiber-pigtailed semiconductor optical amplifier to increase the power to above 20 mW. However, the size of the whole system will increase a lot, making it impossible to be hand-held or mobile. The second option is to improve the device design on a PIC and make it to be able to generate THz beat note with enough power.

Figure 3. Mask layout of high output power THz beat note generation device. (ESOA: Equalizing SOA)

The device on our second PIC is shown in Figure 3. It includes two DBR lasers with Bragg wavelength of DBR gratings at 1548 and 1556 nm respectively. The DBR gratings in the lasers have imbalanced lengths, with a shorter grating length of 100 μm in the front to make sure as much power as possible coming out from the front-grating side [9]. There are two shorter SOA with same length of 400 μm connecting to output of the lasers. These can be used to equalize the output power from the two lasers. After that, there is a 2×2 MMI combining them together to generate beat note, and on-chip boost amplifiers being used to boost the optical power of the beat note for both outputs of the MMI.

We could tune the THz beat note frequency in a similar way as we have shown in the previous section but achieved a more limited tuning range. In the following part, we will demonstrate our measurement results about the output power.



(a) (b)

Figure 4. (a) LIV-curves of two DBR lasers measured separately from the device. (b) Each curve shows with a specific output power from DBR1556 nm laser, the power increase by using ESOA with different current density. The legends show the current injection to the SOA of the laser, and the relevant laser output power could be found from (a).

In order to know the output power from the DBR lasers, we swept the current injection to the SOAs in the lasers and measured their output power, by giving -4 V reverse bias voltage on the corresponding equalizing SOA (ESOA) and using it as a photodiode to monitor the generated current. This can be translated into optical power assuming an efficiency of 0.95 A/W [8]. The results are plotted in Figure 4(a). The maximum output powers of the DBR1556-nm laser and DBR1548-nm laser are 26 and 27 mW respectively. The threshold current levels are 17 and 18 mA respectively. Then we varied the current injection to the SOA of the DBR1556-nm laser from 20 to 120 mA, with a step of 5 mA. For each of these SOA current injection settings, we swept the current injection to the ESOA ranging from 0 to 96 mA. The output power was than measured by giving -4 V reverse bias voltage on the 1000 µm length boost amplifier and using it as a photodetector. The measurement results are shown in Figure 4(b). From this figure, we can conclude that we can use ESOAs as either attenuators or boost amplifiers to equalize the output power levels of two DBR lasers.

3. Discussion

From the results in Figure 4 we can conclude that we can generate over 20 mW optical output power at each lasing wavelength without using the booster amplifiers. Since boost amplifiers in this device will work in a similar way as ESOA, we could estimate that we are able to generate THz beat note signals with optical power above 20 mW from the device on our second PIC. However, we indeed notice some issues. Firstly, even though the center wavelength difference of these two DBR lasers is around 7 nm, enabling us to generate beat notes in the THz range, the wavelength tunability of them is smaller compared to similar lasers on our previous PICs. This limits the frequency tunability of the beat note. We plan to measure the power transmission and reflection spectra of the DBR gratings in the lasers to explore this problem deeper. The second problem is how to minimize the influence of the thermal effects on the device performance, since all components are controlled by current injection, which will create more heating on the PIC with higher current injection.

4. Conclusion

In this paper, we have experimentally investigated the possibility to generate tunable THz beat note by using a monolithic PIC. We could generate THz beat note with a frequency tuning range from 750 GHz to 963 GHz, with the device on our first PIC. However, the output power from it could not feed a commercial PCA to generate THz waves. We improved our device design on our second PIC. The measurement so far shows that it will be possible to generate a tunable THz beat note with optical output power over 20 mW. Additional experimental characterization to get the full tuning map is still ongoing.

Acknowledgement

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