Integrated Terahertz Waveguides and Microcavity Resonators

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Abstract

In the last few years, terahertz (THz) technologies have been extensively explored for applications in chemical and biological sensing, spectroscopy, medicine, and imaging [1, 2]. Integrated THz platforms are highly desirable for chemical and biological detection because they can provide field confinement and enhancement to increase sensitivity [2]. Some such platforms, including one dimensional (1D) parallel-plate waveguides with embedded photonic bandgap structures [3-6] and integrated microstrip resonators [7], have already been experimentally realized. Our research is focused on the development and measurement of integrated THz photonic devices. In particular, we are studying air-core metallic microcavity resonators coupled to rectangular metal waveguides [8] and 1D Bragg gratings embedded in rectangular metal waveguides. Such hollow-core THz microphotonic structures can be ideal for narrow-band sensing applications.

Summary of Research

Figure 1 shows a schematic of a typical device as well as a scanning electron microscopy (SEM) image of a waveguide-coupled microresonator. The THz electric field is polarized vertically with respect to the waveguide walls and propagates in the fundamental TEM-like TE10 mode. The THz time-domain spectrometer (TDS) used in this work was based on a SI-GaAs photoconductive emitter and a silicon-on-sapphire photoconductive detector pumped by a 90 fs Ti:sapphire ultrafast laser (780 nm, 10 mW) [6]. The TDS had a bandwidth of 3 THz and an amplitude spectral dynamic range exceeding 3000. Terahertz pulses from the spectrometer were coupled into and out of the photonic devices using hyperhemispherical Si lenses.

The integrated air-core THz waveguides and resonators were fabricated from highly doped 3 in Si wafers. Devices were patterned into the wafers using standard contact photolithography and deep-RIE Bosch etching. Next, the wafers were oxidized and metallized conformally with Ti/Au (50 nm/400 nm). Finally, two wafers, one with the patterned devices and one blank, were bonded at a temperature of 350°C and a pressure of 1.5 MPa for 45 minutes [9], then diced and polished. A photograph of the facet of a completed 2D rectangular metal waveguide is shown in Figure 1. The waveguides are generally 200 μm wide and 150 μm tall.

We have also fabricated rectangle metal waveguides with embedded 1D Bragg gratings. These gratings exhibit strong photonic bandgaps and can be combined with defect cavities to form high \( Q \)-factor resonators. The fabrication of these gratings is similar to the side-coupled cavities mentioned above with the exception that it requires one additional photolithography step and one additional etch. Initially, 25 μm deep grating teeth are defined and etched in a 3” Si wafer. Next, the waveguide pattern is aligned to the grating teeth and the whole structure is etched an additional 100 μm in the deep-RIE Bosch etcher. The resulting structure is a 125 μm deep waveguide with a 25 μm tall grating embedded in its bottom. An SEM is shown in Figure 2.

Figure 3 displays a typical time-domain scan of the THz electric field and the accompanying power spectrum of a pulse from the spectrometer after propagation through a
waveguide coupled to a 125 µm x 125 µm square cavity. The waveform displays long ringing due to waveguide dispersion as well as the frequency-dependent transmission of the resonator (the secondary pulse at 50 ps is due to reflection off of the waveguide facets). A dip in the power spectrum at 1.33 THz is observed due to excitation of the resonator.

Square metallic cavities of dimensions 175 µm, 150 µm, and 125 µm wide have already been studied. The resonators were coupled to the waveguides via apertures. The size of the coupling aperture of each cavity was varied between 100 µm, 90 µm, and 80 µm (see Figure 1). Figure 4 shows the extracted experimental resonances for all three cavity sizes. The power transmission, T, of a resonator has a Lorentzian shape given by [10]:

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T = \left| 1 - \frac{1}{Q_C} \right|^2 \left( \frac{1}{Q_C + \frac{1}{Q_L} - 2j(1 - f)} \right) \]

where \(f\) is the center frequency of the resonance and \(Q_C\) and \(Q_L\) are the cavity Q-factors due to waveguide coupling and loss, respectively. This model was used to fit to the experimental data and the results are shown in Figure 4. The resonance frequency increases with decreasing cavity size and decreasing aperture size, which is in good agreement with the trends predicted by 2D finite-difference time-domain (FDTD) simulations. From Figure 4, we conclude that the total Q-factor of these integrated metallic cavities is less than 50 and is limited by cavity loss. Cavity losses are expected to be dominated by ohmic losses in the metal sidewalls.

**References**