Photonic Crystal Resonators as Bio-liquid Sensing Platforms in the Terahertz Band

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Abstract

We describe the development of high quality (Q) factor photonic crystal resonators (PCRs) integrated with microfluidic systems to form the basis of highly sensitive liquid sensing platforms for the terahertz band. The strong confinement of the terahertz field in combination with the high Q-factor provided by the PCR allows the measurement of the dielectric properties of sub-nanoliter liquid volumes. We demonstrate the utility of this approach by measuring the complex permittivity of several bio-liquids at 100 GHz.

1. Introduction

PCRs have a well-established ability to achieve ultra-high Q-factors while simultaneously confining optical and infrared light to near- or sub-wavelength volumes. This feature makes them ideal sensors for samples with volumes less than λ^3. In the terahertz band, PCRs are less well developed despite the possibility of offering some of the highest Q-factors at room-temperature.

In this paper, we demonstrate the realization of several different types of PCRs operating at 100 and 200 GHz. We show that these resonators when combined with microfluidics allow the extremely sensitive detection of a liquid analyte's complex permittivity through enhancement of the strength of interaction between the liquid and the PCR's resonant mode.

2. High-Q terahertz PCRs

We can have experimentally demonstrated both microbeam and slab type PCRs for the low terahertz band and they will now be discussed individually.

2.1. THz Microbeam PCRs

A 1D or microbeam PCR can be fabricated from a rectangular dielectric slab waveguide by exploiting the transverse waveguide (TE) bandgap induced in the waveguide through the introduction of a linear array of cylindrical air holes. Through careful design of the hole radii and positions, a localized defect state can be created which supports a resonant mode with a ultra-high Q-factor [1].

We have experimentally demonstrated microbeam PCRs operating at 100 and 200 GHz [2], recently achieving Q-factors as high as 22,000. Figure 1 shows one of the fabricated microbeam PCRs. The central microbeam is suspended using a series of supporting struts which electromagnetically isolates it from its environment, reducing dielectric losses and maximizing its Q-factor.

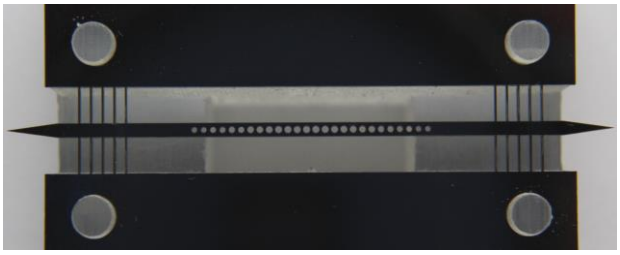

Figure 1: A one-dimensional microbeam PCR with a resonant frequency of 100 GHz.

2.2. THz Slab PCRs

A commonly implemented PCR is the slab PCR, which exploits the 2D TE bandgap created in a dielectric substrate when a periodic array of air holes is introduced. We realized a PCR resonating at W-band by creating a L3 cavity defect (three omitted holes) in a triangular lattice of holes etched in a high resistivity silicon substrate as shown in Fig. 2. The resonant defect was excited using a W1 defect waveguide, created by omitting a line of holes in the lattice. A Q-factor of approximately 11,900±500 was demonstrated, limited by the dielectric loss in the silicon [3].

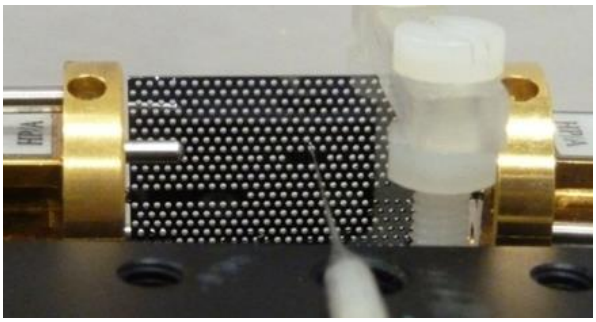

Figure 2: A two-dimensional photonic crystal slab resonator designed for W-band operation suspended between two waveguide flanges. A capillary tube is used to flow liquids through the field of the resonant mode.

2.3. PCR Fabrication

Both the microbeam and slab PCRs were fabricated using the Bosch process to perform deep reactive-ion etching (DRIE) of the 525 µm thick silicon wafer (resistivity >10 kΩ·cm) to realize the high aspect ratio holes with nearly vertical sidewalls.

3. Liquid Sensing

The PCRs were integrated with microfluidic systems to enable their use as liquid sensing platforms. A microfluidic syringe pump and quartz capillaries with 100-200 µm diameter were used to flow liquid analytes close to or through the high intensity region of the electric field of the PCR's resonant mode.

The introduction of the liquid analyte modifies the resonant modes properties. Perturbation theory can be used to relate a change in the PCR's resonant frequency Δf and reciprocal Q-factor $\Delta(1/Q)$ to the complex permittivity ϵ_s of a liquid analyte introduced into the field of the PCR. By assuming a quasi-static approximation for the electric field inside the liquid sample, the following analytical expression can be derived [4]

$$\frac{\Delta f}{f_0} + \frac{i}{2}\Delta\left(\frac{1}{Q}\right) \approx -A\frac{\epsilon_s - B}{\epsilon_s + \epsilon_q} \qquad (1)$$

where ϵ_s and ϵ_q are the liquid sample and quartz capillary permittivies, respectively, and *A* and *B* are the coefficients determined through fitting the measured response of binary solutions of water-ethanol solutions of known permittivity.

3.1. Bio-liquid and cell sensing

Once the system is calibrated and the fitting coefficients determined, the PCR can then be used to characterize the permittivity of unknown liquid analytes. As an initial demonstration, we characterize the constituents of human blood at 100 GHz using the slab PCR. We prepared cell suspensions of white (0.5% vol.) and red (50% vol.) blood cells and measured relative complex permittivities of 8.6±0.4+i(14.2±2) and 8.2±0.4+i(11.4±2), respectively. The blood plasma was measured to have a permittivity of 8.7±0.4+i(13.6±2).

3.2. Toward single biological cell sensing

The sensitivity provided by the use of a high-Q PCR can be leveraged for the detection of sub-wavelength particles in a liquid. An important application of this is the dielectric measurement of single biological cells in a culture medium. To achieve this, we have designed improved PCRs which confine the field to smaller modal volumes and improved the microfluidics to allow smaller diameter capillary tubes to reduce the liquid interaction volume. Initial measurements have shown this approach to be capable of detecting individual cells. The potential advantage of this approach is that it allows non-invasive, label-free and contactless cell analysis to be made in real-time

4. Conclusions

We have demonstrated microbeam and slab type PCRs for the terahertz band, realizing Q-factors as high as 22,000 and limited by dielectric loss in the silicon. By combining these resonators with microfluidic systems, we have created sensing platforms for the measurement of the dielectric properties of nanoliter and sub-nanoliter quantities of liquids. This result represents a step towards a lab-on-a-chip device for the analysis of bio-liquids at terahertz frequencies

Acknowledgements

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