

TERAHERTZ PHOTONIC CRYSTAL TECHNOLOGY

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Abstract - Within this work we show the potential for photonic crystal technology fabricated from high resistivity silicon for THz applications. This technology is usually associated with optical wavelengths but, by scaling down in frequency, we show through simulations and experimentally measured prototypes how simple waveguides can be realised. These can then be used to create switches and attenuators, through laser illumination of the waveguide. Furthermore, we show how this technology can be used to realise unprecedented Q-factor performance for resonators that are suitable for monolithic integrated circuits.

Photonic Crystal Lattice Design

A photonic crystal (PC) is a structure that has an engineered variation in permittivity in one, two or three dimensions, creating an electromagnetic bandgap (EBG) that can be complete or just TE- or TM-like [1]. All the PCs described in this work have a bandgap created through a triangular lattice of air holes within a high resistivity silicon (>10 k Ω .cm) substrate. The lattice used for waveguide simulations and resonator structures can be seen in Fig. 1. It has a lattice constant of 780 μ m, with 235 μ m radius air holes (the dimensions for the switch optimized for a lower frequency is described later). Additionally, to allow for experimental measurement, a coupling taper is required to couple from a WR-10 waveguide to the PC. This was realised through a 2.1 mm by 1.2 mm triangular taper at both ends. This structure was then simulated using CST Microwave Studio with WR-10 waveguides and associated flanges simulated as PEC. The results are shown in Fig. 1, showing the E-field magnitude. Above and below the bandgap, the field propagates through the lattice but not within the bandgap, which is from 97 – 127 GHz.

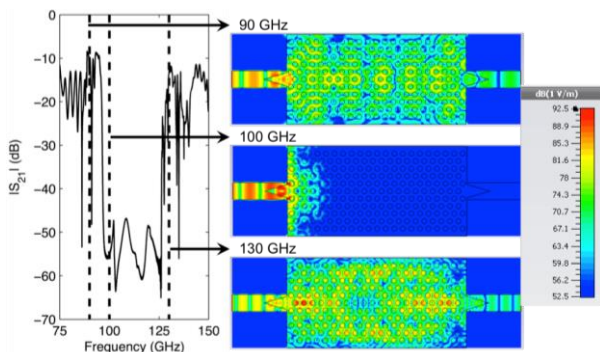


Figure 1: Simulation showing the bandgap created by the PC lattice with E-field magnitudes below, at and above the bandgap, respectively

Waveguide

A PC waveguide is created by removal of a single row of holes, within the lattice, to form a W1 defect waveguide. This is the simplest defect to add to the PC and provides the basis for all other devices. Figure 2 shows the simulated transmission through such a waveguide, where it is clearly seen from the E-Field plots that within the bandgap transmission is through the waveguide. The operating band is approximately 100 – 125 GHz, as seen in Figs. 1 and 2.

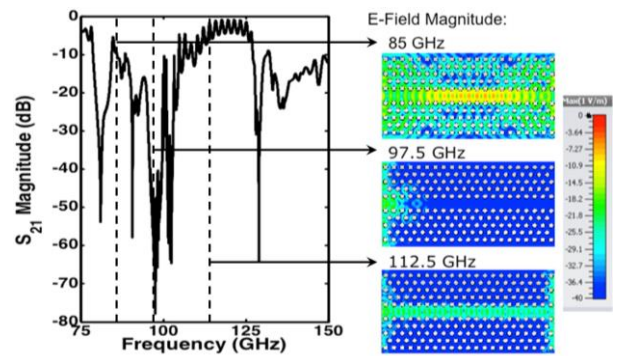


Figure 2: Simulation showing the W1 defect transmission with E-field magnitude plots showing unguided transmission below the bandgap, no transmission in the bandgap and guided transmission in the bandgap (top to bottom)

Attenuators [2]

The PC with a defect waveguide can behave as a millimetre-wave attenuator. The level of the attenuation is controlled by modulating the local conductivity of the silicon inside the W1 defect waveguide through optical illumination. Figure 3 shows the experimental setup used to measure this device using a VNA and a pair of infrared laser diodes.

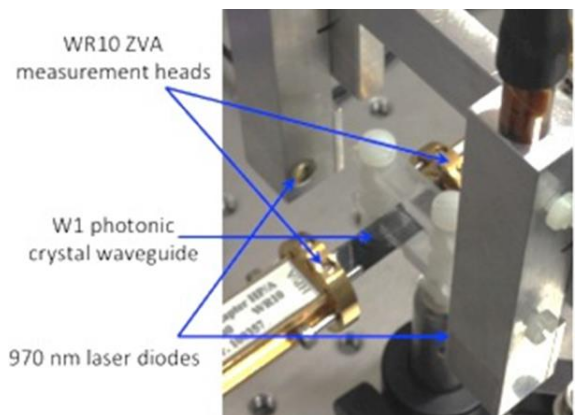


Fig. 3: Measurement setup for attenuator

Measured results in Fig. 4 show that an attenuation >40 dB can be achieved across the band, with up to 60 dB at specific frequencies.

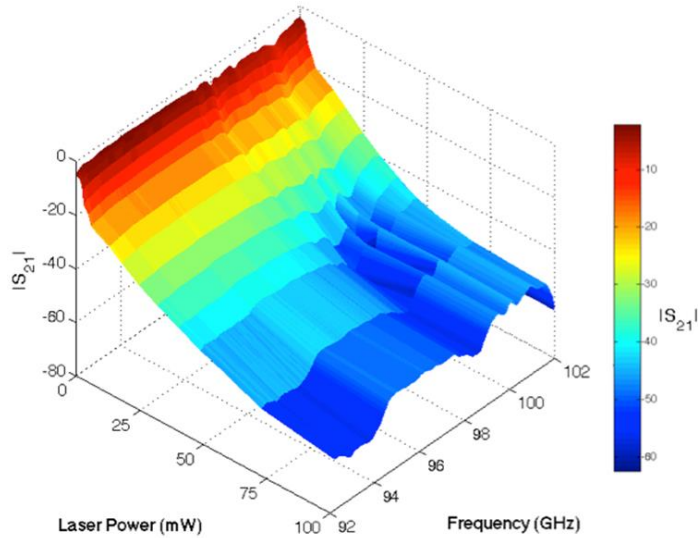


Figure 4: Measured data showing the transmission through the W1 defect waveguide as a function of illuminating laser power

Resonators [3]

Resonators designed to operate at a frequency of 100 GHz are presented in this section. The resonators are formed from L3 defect cavities (removal of three adjacent air holes) and fed via W1 defect waveguides. To increase the Q-factor of these cavities, the three air holes on either side of the cavity are shifted so that out-of-plane radiation is minimised [4]. Three different feed geometries, illustrated in Fig. 5, were measured: inline, offset and a weakly coupled design [3].

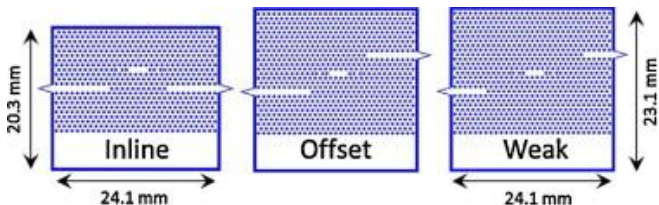


Figure 5: Three PC defect resonators with different coupling geometries. (left) inline coupling; (middle) offset coupling; (right) weak coupling

Measured results were obtained using a VNA, with a pair of WR10 waveguide frequency multiplier heads; calibrated across W-band using the Thru-Reflect-Line method. The S-parameter results are shown for the three resonators in Fig. 6. The strongly coupled offset resonator has a loaded Q-factor $Q_L = 5,220$; the strongly coupled inline $Q_L = 4,130$; and the weakly coupled offset $Q_L = 7,090$. These can then be used to calculate the unloaded Q-factor of the resonator as $9,040 \pm 300$. This extremely high Q-factor resonator can be used to realise important components for future millimetre-wave and terahertz communication and radar systems, such as low phase noise oscillators and band pass filters.

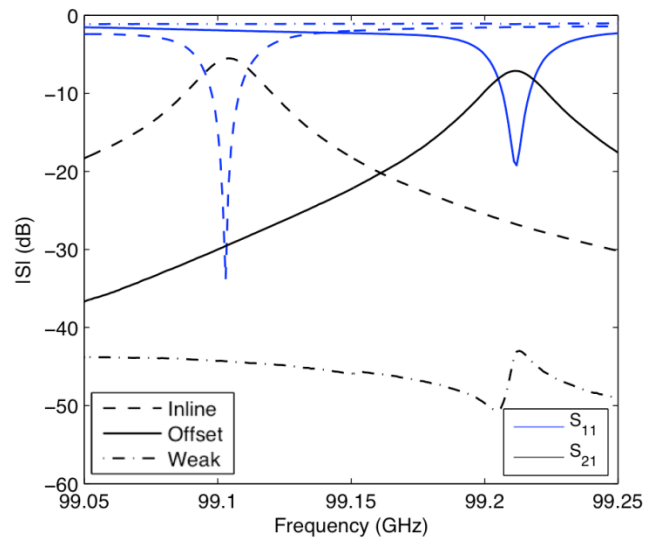


Figure 6: Measured S-parameters for the three resonator designs

Conclusion

This work demonstrates the potential for photonic crystal technology operating at THz frequencies. We presented the basic system components: a waveguide, a variable attenuator (based upon laser-induced photoconductivity) and resonators, which can be used in a system's front-end architecture. The results of these initial prototypes show very promising performance, with >40 dB extinction ratio in the double-sided illuminated attenuator and a resonator loaded Q-factor of 5,000; have both been shown experimentally. This offers the prospect of being able to create monolithically integrated THz circuits with exceptional performance in an area that is currently perceived as a technological bottleneck in silicon integrated circuit technology.

References

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