100 GHz PHOTONIC CRYSTAL DEVICES

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Abstract

Within this paper we show the potential for high resistivity silicon photonic crystal devices at 100 GHz (i.e. W-Band). This technology is usually associated with optical wavelengths. However, by scaling down in frequency, we show through simulations and measured demonstrators how simple waveguides can be realised which can then be used to create switches and attenuators through laser illumination of the waveguide. Furthermore, we go on to show how this technology can give unprecedented Q-factor performance for millimetre wave resonators/filters 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 or more spatial dimensions, creating an electromagnetic bandgap (EBG) in transverse electromagnetic (TEM), transverse electric (TE) or transverse magnetic (TM) in nature \cite{1}. All the devices described in this work are 2D PCs with the bandgap created through a triangular lattice of air holes within a high resistivity silicon (HRS) substrate. The lattice used for waveguide simulations and filter structures can be seen in Fig. 1. It has a lattice constant of 780 µm and the air holes have a diameter of 470 µm (the lattice dimensions for the switch, which is optimized for a lower frequency, is described later). Figure 1 shows simulations using \cite{2}, where the lattice has a TE-like bandgap from 97-127 GHz.

Figure 1: Band diagram for the photonic crystal showing the TE-like modes (blue) and TM-like modes (red dashed). The bottom right inset shows the crystal lattice structure and the bottom central inset shows the lattice Brillouin zone.
For experimental measurements an additional coupling taper is employed to couple from a standard WR-10 waveguide to the substrate integrated waveguide (SIW) PC. This was realised through a 2.1 mm by 1.2 mm triangular coupling taper at either end. This structure was then simulated using CST Microwave Studio with WR-10 waveguides and associated flanges simulated as a perfect electrical conductor (PEC); the results are shown in Fig. 2, where the E-field magnitude shows how above and below the band gap the field propagates through the lattice but not in the band gap.

![Figure 2: Simulation showing the bandgap created by the PC lattice with E-field magnitudes below, at and above the bandgap, respectively.](image)

**Photonic Crystal Microfabrication**

All the devices described within this work were fabricated from 100 mm diameter HRS wafers of thickness 525 μm ± 5 μm and resistivity > 10 kΩ-cm. Silicon was the preferred substrate, due to its low loss at 100 GHz (tan δ ~ 10^-4), high effective relative permittivity 11.64 [3]. This choice provides a good contrast with the surrounding air interface, to reduce the angle for total internal reflection, its compatibility with micromachining and potential for monolithic integration.

The fabrication steps are shown in Fig. 3. The processing was undertaken using standard micromachining processes. Initially a thick layer (10 μm) of photoresist (AZ9260) is spun on the wafer and the design is transferred using an acetate film mask with standard photolithography techniques. The first etch of the wafer was to two thirds of the way through using deep reactive ion etching (DRIE), which involves alternating between SF₆ plasma etch and deposition of C₄F₈ passivation layer. The control of the timings of each of these phases affects the verticality of the sidewall and also the scallops in the sidewall. A backing wafer of low-cost single-side polished silicon was attached temporarily to the HRS wafer, using a thermally conducting paste, before etching the final third of the way through the wafer (providing protection to the DRIE chuck). Once the etching has been, the PC’s are manually removed from the backing wafer and cleaned through rinses in Isopropyl alcohol (IPA) and acetone. Figure 3 shows the sidewall profile and circularity of the holes when inspected under and scanning electron microscope (SEM). The main defects in the sidewall are caused by the resolution of the acetate masks; this can be improved by using higher resolution chrome/glass masks.
Waveguide Demonstrator

A PC waveguide is created by removal of a single row of holes within the lattice, to form a W1 defect. This is the simplest defect to add to the PC and provides a basis for all other devices to be created. Figure 4 shows the simulated transmission through such a waveguide using CST Microwave Studio. It is clearly seen that, within the band gap, transmission is through the waveguide from the E-Field plots. The operating band is approx. 100-125 GHz when compared to Fig. 2.

Figure 4: Simulation showing the W1 defect transmission with E-field magnitudes showing unguided transmission below the bandgap, no transmission in the bandgap and guided transmission in the bandgap.
Photonic Switch Demonstrator [9]

This section demonstrates the PC with a defect waveguide that can behave as a millimetre-wave switch. The state of the switch is controlled by modulating the local conductivity of the silicon inside the defect waveguide through optical illumination. The PC is of the same type previously mentioned; a 2D triangular lattice of cylindrical air holes, however, now the operating range is from 90 to 100 GHz. This is created by changing the cylinder radius to 270 μm and the lattice constant to 900 μm for the same 525 μm thick HRS wafer.

Simulated results of the PC across the WR-10 band were obtained using ANSYS® HFSS™ version 13.0. The HRS is modeled with $\varepsilon_{\text{reff}} = 11.64$ and $\tan\delta = 10^{-4}$ [3]; the air cylinders are represented by a vacuum and the WR-10 feed waveguide walls as PEC. The laser was modeled as a cluster of small spots on both sides of the W1 defect waveguide, producing a total illumination area of 2 mm$^2$ on both sides. The conductivity profile for this is taken from [4, 5], which had been simulated using the SilvacoTM 2D Luminous solver. The HFSS™ results in Fig. 5 show that the PC has a 85-105 GHz band gap. Within this, the W1 defect waveguide operates over the 88 to 98 GHz frequency range, having a predicted insertion loss of less than 1.5 dB across this band.

When the simulated laser illumination, having a wavelength of 808 nm and power density of 80 W/cm$^2$, is applied then the insertion loss increases to over 44 dB. This represents a greater than 40 dB reduction in the power transmittance through the crystal.

The switching response was then measured using the setup shown in Fig. 6, which consisted of a 91.898 GHz Millitech GDM-10-0-17H WR10 Gunn diode source [6] and external isolator. The PC was inserted between the isolator and a Millitech DXP-10 Schottky barrier lead diode detector [6]. The PC is aligned so that it sits in the centre of the rectangular waveguides, with the HRS coupling tapers protruding fully inside. The output of the detector is measured using a Marconi Instruments VSWR meter, having an internal variable attenuator. The laser illumination is provided by a pair of IPG Photonics PLD-33 laser diodes [7], which produce a spot diameter of ~1.5 mm on each side of the PC, as shown in Fig. 7.
A reference measurement for transmission was established by removing the PC and connecting the isolator directly to the detector. The laser current was swept from 0 to 1 A, to obtain the switching performance of the PC, with the measured results shown in Fig. 8. It can be seen that an extinction ratio of 40.1 dB exists between the ON and OFF states, which is in good agreement with the simulation data presented in Fig. 2. Figure 5 also shows that the illuminating power required from the laser, to significantly switch the state of the PC waveguide, is ~ 100 mW. It can be seen that as the laser power increases beyond this; the transmission drops further, as the local plasma conductivity in the silicon increases further, but then saturates at -40.1 dB. This represents the background level of the other leakage radiation paths through the PC.
Filter Demonstrator [10]

Millimetre-wave and terahertz (THz) frequencies are attractive for the design of high performance filters in communications, radar and sensor applications. Table 1, shows how the performance of the state of the art compares with the two PC filters (band reject and band pass) with a designed operating frequency of 100 GHz presented in this section.

L3 defect resonant cavities (created by removal of three adjacent air holes) are introduced to the lattice as they will provide the filtering at ca. 100 GHz. To increase the Q-factor of these cavities, the three air holes either side of the cavity are spatially shifted so the field is more gently confined [6]. To realize a band reject filter from this cavity a W1 waveguide defect is added to the lattice, two rows below the cavity. Similarly the band pass filter is realised by adding two W1 defect waveguides that do not completely pass across the crystal, so energy has to couple from the input W1 defect, then through the cavity to an output W1 defect. Again coupling tapers to WR-10 waveguides are employed.

Measured results were obtained using a Rohde and Schwarz ZVA with WR-10 multiplier heads and a calibrated using a thru, reflect and line (TRL) method. The experimental setup is shown in Fig 10.
The S-parameter results are shown for both filters in Fig 11. The band reject filter has a 3 dB fractional bandwidth of 0.1% with 30 dB rejection at 99.74 GHz. This gives the filter a loaded Q-factor of 1,000. The band pass filter has a 3 dB fractional bandwidth of 0.024% giving a loaded Q-factor of 4,000. The difference in the fractional bandwidths and loaded Q-factors, with both cavities being identical, is due to the weaker coupling to the cavity for the band pass filter; meaning that the loaded Q-factor approached that of the unloaded Q-factor.

Conclusion

The experimental research presented shows the real potential for photonic crystal devices at millimetric frequencies, which includes a waveguide, a photonic switch and filters. The results show excellent performances, with a >40 dB extinction ratio in the double-sided illuminated switch and a filter loaded Q-factor of 4,000. This offers the prospect of being able to create monolithically integrated mm-wave circuits with exceptional performance in an area that is currently perceived as a technological bottleneck in silicon integrated circuit technology.

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References


[6] [http://www.millitech.com](http://www.millitech.com)

[7] [http://www.ipgphotonics.com](http://www.ipgphotonics.com)

