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Optical Switching of 1-D Microstrip Photonic Bandgap Structures

Darren Cadman, Robert Miles, Robert Kelsall and David Hayes

Abstract—The optical control of a microstrip one dimensional (1-D) photonic bandgap (PBG) structure has been demonstrated over the frequency range 7-13GHz. A microstrip PBG structure was fabricated on Duroid 6010 and a high resistivity photoconductive Si wafer was placed in contact with the ground plane. With no optical illumination incident upon the Si, the microstrip PBG filtering properties are well-defined. When the Si is illuminated the filtering properties are suppressed. Under illumination the experimental results display an increase in S_{21} of 6.5dB and a reduction in S_{11} of more than 8dB at the centre frequency of 10GHz. Experimental results are presented alongside those simulated.

Keywords—Microstrip, optical control, periodic structures, photonic bandgap (PBG), photoconductivity, plasma, silicon.

I. INTRODUCTION

THE concept of a Photonic Bandgap (PBG) structure for microstrip technology was first introduced and realized by Qian *et al.* in 1997 [1]. Previous to that, research on PBGs had been primarily focused in the optical regime [2]. The microstrip PBG structure in [1] consists of holes drilled through the microstrip substrate to form a periodically spaced honeycomb lattice. The fabrication of microstrip PBGs was made easier with the realization that they could be fabricated by etching holes in the ground plane thus removing the need to drill holes through the substrate. An added advantage of this fabrication method is improved stopband characteristics in terms of depth and width [3]. There has been much research into the topic of microstrip PBGs with regard to, for example, different hole patterns and shapes and their associated filtering properties [4][5] and ap-

plications, such as the suppression of harmonic frequencies [6][7].

To date the optical control of microstrip PBGs has not been reported. However the optical control of microwave circuits has been reported previously and the frequency of published articles has increased over the past 5 years. Applications include the optical switching of frequency selective surfaces [8][9], optically controlled steerable microwave antennas [10] and the optical control of co-planar waveguide Bragg gratings [11]. Each of these applications exploit the change in a semiconductor's conductivity when it is irradiated with photons of energy greater than its bandgap energy.

In this paper, simulated and experimental results are presented for a microstrip 1-D PBG structure with optical control.

II. PLASMA IN SEMICONDUCTOR MATERIAL

An unilluminated semiconductor can be regarded as a dielectric material especially if it is of a high purity. Under illumination electron-hole pairs are generated forming a conducting plasma that at sufficiently high excess carrier densities can appear to be metallic to an electromagnetic wave. The generation of electron-hole pairs modifies the relative permittivity of the Si, as described by [12]:

$$\epsilon_r = \epsilon_L \epsilon_0 - \sum_{i=e,h} \frac{\omega_p^2}{\omega^2 + (\frac{1}{\tau_i})^2} \left(1 + j \frac{1}{\omega \tau_i} \right) \quad (1)$$

where ϵ_L is the dielectric constant of the host lattice (11.9 for Si), ϵ_0 is the permittivity of free space, ω is the radial frequency, τ_i is the mean time between collisions for the carriers and ω_p is the plasma frequency as given by:

$$\omega_p = \sqrt{\frac{nq^2}{\epsilon_0 m_i^*}} \quad (2)$$

in which n is the plasma density, q is the electronic charge and m_i^* is the effective mass of the

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carrier. At high levels of generation the mean time between collisions decreases as more coulomb interactions occur. As a result the mobility of the carriers decreases [13]. Fig 1 shows that at low excess carrier densities the real part of the permittivity dominates and the Si is in its dielectric regime. At high levels of excess carrier density the imaginary part is dominant and the Si acts as a conductor. The photogenerated conductivity, $\hat{\sigma}$,

Fig. 1. Variation of permittivity with excess carrier density for Si at 10GHz

of the Si is plotted against excess carrier density in Fig. 2 for high excess carrier densities and was calculated using:

$$\hat{\sigma} = q\hat{n}(\mu_e(\hat{n}) + \mu_h(\hat{n})) \quad (3)$$

where $\hat{n}$ is the excess carrier density and, μ_e and μ_h are the excess carrier dependent mobilities as given by [13].

III. PBG DESIGN

The microstrip PBG structure illustrated in Fig. 3 was designed for operation over a frequency range of 7-13GHz with a centre stop-band frequency $f_c=10\text{GHz}$. It was fabricated on RT/Duroid 6010 ($\epsilon_r = 10.2$) with a single row of 6 circular holes etched in the ground plane directly under the microstrip line. The holes were equally spaced a distance a apart where $a = \lambda_g/2$ and λ_g is the guided wavelength at f_c . The hole radius r was $r = 0.3a$. The microstrip line width was calculated using conventional microstrip design equations to give a line impedance of 50Ω at 10GHz. A high resistivity ($\rho_{Si} = 60 \Omega\text{m}^{-1}$) FZ

Fig. 2. Si conductivity versus excess carrier density accounting for Coulomb interactions at high injection levels

n-type Si slice was placed beneath and in contact with the microstrip PBG ground plane. The Si was $400\mu\text{m}$ thick and its effective carrier lifetime was 1-10ms.

Fig. 3. Microstrip 1-D PBG with photoconducting ground plane

IV. SIMULATED RESULTS

Using Agilent HFSS, the structure in Fig. 3 was simulated for a range of values of Si conductivity that represented varying degrees of optical illumination and excess carrier density. In each case the photogenerated plasma was assumed to be uniform throughout the Si. In Figs. 4 and 5 simulated S-parameter results are plotted for several values of Si conductivity. In the simulations the unilluminated case was represented by a Si conductivity $\sigma_{Si} = 16 \text{ mSm}^{-1}$. To represent varying degrees of optical illumination Si conductivity values of 10, 50, and 500 Sm^{-1} are plotted; the higher the value

for σ_{Si} , the higher the level of illumination. Fig. 4 shows that as σ_{Si} increases the magnitude of the reflection coefficient decreases. From Fig. 5 it can be seen that for $\sigma_{Si} \geq 50 \text{ Sm}^{-1}$ the magnitude of the transmission coefficient improves at f_c with increasing σ_{Si} . At high Si conductivities the band-stop filtering properties are suppressed and the Si acts as a complete conducting ground plane. Fig.

Fig. 4. Simulated S_{11} of 1-D microstrip PBG for several values of Si conductivity

Fig. 5. Simulated S_{21} of 1-D microstrip PBG for several values of Si conductivity

6 displays how the loss of the structure varies with Si conductivity at 10GHz. The loss of the structure was calculated from:

$$Loss = 1 - (|S_{11}|^2 + |S_{21}|^2) \quad (4)$$

It can be seen that the loss is at a maximum when the conductivity of the Si is $30 - 50 \text{ Sm}^{-1}$. At

conductivities less than this the filtering properties of the PBG are still visible. However at values of $\sigma_{Si} > 50 \text{ Sm}^{-1}$ the loss decreases with increasing σ_{Si} and the structure starts to behave more like a conventional microstrip line.

Fig. 6. Loss of optically controlled 1-D microstrip PBG calculated for a range of Si conductivities at $f_c = 10\text{GHz}$

V. EXPERIMENTAL RESULTS

The experimental results in Figs. 7 and 8 show that in the dark, the microstrip PBG acts as a bandstop filter with a 3dB bandwidth of 2.5GHz and stopband depth of -12dB at 10GHz. These results are in good agreement with the simulated. When the Si is optically excited by light from a halogen bulb, the conducting plasma formed within the Si suppresses the bandstop characteristics. An increase in the transmission coefficient of 6.5dB and a decrease of 8dB in reflection coefficient are observed at 10GHz. Comparison of simulated results with experimental show that the photogenerated conductivity is $100\text{-}200 \text{ Sm}^{-1}$ which from Fig. 2 corresponds to an excess carrier density in the range $4 \times 10^{21} \text{ m}^{-3} < \hat{n} < 10^{22} \text{ m}^{-3}$.

VI. CONCLUSIONS

The optical control of a microstrip 1-D PBG circuit has been demonstrated. Initial experimental results suggest that a Si conductivity in the range $100\text{-}200 \text{ Sm}^{-1}$ has been achieved. With a higher excess carrier density it is expected that the band-stop characteristics can be suppressed further and a reduction in the loss of the circuit will result.

Fig. 7. S_{11} experimental results of optically controlled microstrip 1-D PBG compared with simulated results

Fig. 8. S_{21} experimental results of optically controlled microstrip 1-D PBG compared with simulated results

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