Millimeter-wave negative group delay network

(Invited)

William J. Otter, Stephen M. Hanham, Norbert Klein and Stepan Lucyszyn
Centre for Terahertz Science and Engineering
Imperial College London
London, UK
s.lucyszyn@imperial.ac.uk

***Abstract*— This paper describes a negative differential-phase group delay network operating at millimeter-wave frequencies, which can be used to compensate for frequency variations in group delay that may otherwise cause signal distortion. This approach utilizes a defect waveguide with a high Q-factor defect cavity resonator, realized with a high-resistivity silicon-based 2D photonic crystal with engineered waveguide dispersion characteristics. We demonstrate a group delay of -151.8 ns at 99.74 GHz, with a correspondingly high figure of merit value of 3.34.**

Keywords—differential phase negative group delay, millimeter-wave, photonic crystal, EBG

I. Introduction

Group delay compensation, using a negative group delay (NGD) network, is often required to compensate for non-ideal phase-related behaviour of real circuits (such as interconnects, impedance matching networks, filters, mixers and amplifiers); achieving a maximally flat in-band group delay frequency response and, thus, mitigate against related causes of signal distortion. Differential-phase group delay $\tau(\omega)$ is calculated from the gradient of the insertion phase of a 2-port network $\phi(\omega)$ with angular frequency ω, thus:

$$\tau(\omega) = -\frac{\partial \phi(\omega)}{\partial \omega} \quad (1)$$

The principle of creating a negative differential-phase group delay was first demonstrated at microwave frequencies by Lucyszyn *et al.*; with a 1 GHz hybrid microwave integrated circuit implementation employing a microstrip 3 dB quadrature coupler [1, 2]. Over the past two decades, a wide variety of alternative implementations have emerged; divided into the two broad categories of passive and active. NGD occurs when absorption/attenuation is at a peak [3]. This means that most passive designs are created from band-stop type circuits; requiring amplification to overcome the inherent transmission losses, which itself contributes additional positive group delay.

In contrast, active circuits can overcome the inherent losses, to give a zero net insertion loss. Furthermore, it was shown in [1, 2] that the levels of group delay can be tuned by varying the Q-factor of the resonator, using variable resistors (e.g. PIN diodes or cold-FETs); while their frequency can be independently tuned using varactor diodes, as show explicitly in [4].

Table 1 summarizes the performance of various passive and active negative differential-phase group delay synthesizers described within the open literature; giving the resonance/centre frequency f_0; out-of-band differential-phase group delay τ_∞; minimum group delay τ_{min}; associated NGD bandwidth Δf (where $\tau \leq 0$); $|S_{21}(f_0)|^2$ (dB) is the insertion loss at f_0. In addition, we have introduced a new figure of merit (FoM) for comparing NGD networks, which combines the attributes of both the minimum level of group delay with the corresponding NGD bandwidth:

$$FoM = \Delta f |\tau_{min}| \quad (2)$$

From Table 1, it can be seen that the work presented here provides almost twice the FoM performance of previously reported NGD networks.

In this paper, we demonstrate a NGD network at millimetre-wave frequencies, using a defect waveguide structure implemented in a high-resistivity silicon (HRS) 2D photonic crystal (PC), and propose a method where both the frequency and group delay are tuneable.

Table 1: Performance comparison of reported negative group delay networks

Year	f_0 **(GHz)**	τ_∞ **(ns)**	τ_{min} **(ns)**	Δf **(GHz)**	***FoM***	$\lvert S_{21}(f_0)\rvert^2$ **(dB)**	**Active or Passive**	**Reference #**
1993	1	0	-50	0.036	1.80	-45	Active	[1]
2013	1	1	-1.25	0.55	0.69	-10	Active	[4]
2007	1.02	0.2	-2.3	0.35	0.81	-2	Active	[5]
2014	1.96	1.5	-6	0.15	0.90	-36	Passive	[6]
2013	2	0.6	-1.3	0.5	0.65	-25	Passive	[7]
2010	2.14	0	-9	0.03	0.27	0	Active	[8]
2009	3	0.01	-0.025	3.5	0.09	-5	Passive	[9]
2009	21.7	0.04	-0.083	2.5	0.21	-24	Passive	[10]
2016	**99.74**	**0.7**	**-151.8**	**0.022**	**3.34**	**-50**	**Passive**	**This work**

II. Design and Fabrication

PC resonators have been shown to have ultra-high Q-factors in the infrared and W-band [11, 12]. This can produce large NGDs, when a coupling structure implements a band-stop characteristic to create an attenuation maximum [3]. To achieve this characteristic at 100 GHz, we employ a 2D PC, having a triangular lattice of 470 µm diameter cylindrical air holes with a periodicity of 780 µm in a HRS substrate (with $\varepsilon_r' = 11.7$ and $tan\,\delta = 10^{-4}$ [13]). This configuration and dimensions creates a TE-like bandgap at 100 GHz [12]. A W1 defect waveguide is realized by the omission of a single row of air holes, allowing a mode to propagate through the lattice. A band-stop characteristic is achieved with the use of an L3 cavity defect, placed 3 periods above the W1 waveguide defect, as seen in Fig. 1. To measure the device using commercial WR10 (W-band) metal-pipe rectangular waveguide (MPRWG) test heads, triangular coupling tapers of 2.1 mm x 1.2 mm were added to each end of the W1 defect waveguide. These tapers couple energy from the TE_{10} mode of the MPRWG to the W1 defect waveguide mode.

The PC was fabricated by bulk micromachining of a standard 525 µm thick, 100 mm diameter HRS wafer using deep reactive ion-etching. The fabricated device is shown in Fig. 1.

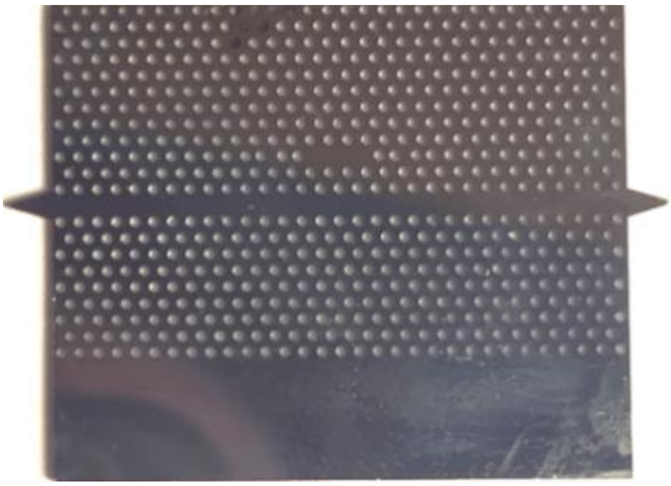

Figure 1: Photograph of the fabricated negative group delay device.

III. Measurements

Measurements were carried out using a Rohde and Schwarz ZVA24 vector network analyser (VNA), with a pair of ZVA-Z110 frequency multiplier test heads attached. A Thru-Offset-Short-Match (TOSM) algorithm was used to calibrate the VNA and define reference planes at the ends of the test head waveguide flanges.

The measured transmission characteristics can be seen in Figs. 2 to 4, having a high frequency resolution of 366.300 kHz. There is a minimum transmission of -49.7 dB at the resonance frequency, $f_0 = 99.74$ GHz and a transmission loss of -11 dB away from resonance. This latter loss is caused by non-optimal coupling tapers between the MPRWG and the W1 photonic crystal defect waveguide and, therefore, does not present an inherent limitation on devices performance, as shown in [12, 14]. Figure 3 shows the insertion (transmission) phase through the structure. There is a steep negative phase slope at f_0; inferring a high Q-factor resonator and a large negative group delay at resonance. Figure 4 shows the differential-phase group delay. The group delay is $\tau_0 =$ -151.8 ns at $f_0 = 99.74$ GHz and $\tau_\infty \approx 0.7$ ns.

The proof-of-principle device has a very narrow bandwidth and operates at a single frequency that has not been tuned. However, it is possible to modify the properties of the PC through photo-illumination [14, 15], by exploiting the inherent photoconductive nature of HRS; changing both group delay and resonance frequency. Alternatively, the PC can be cooled/heated to predominantly shift the resonance frequency.

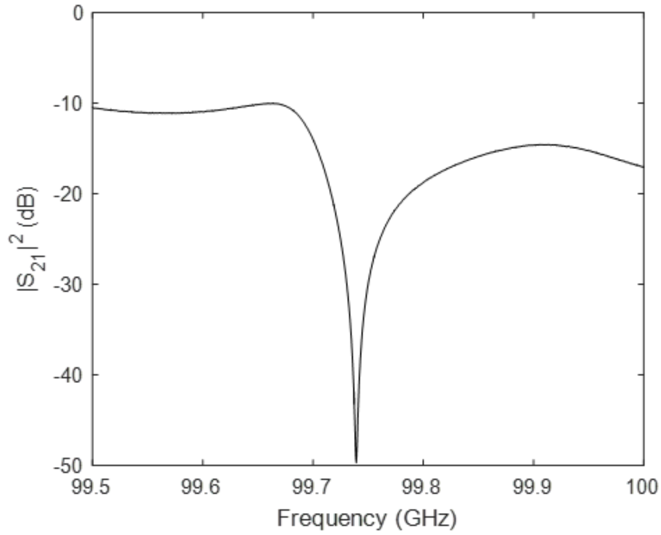

Figure 2: Measured insertion loss of the defect waveguide within the PC.

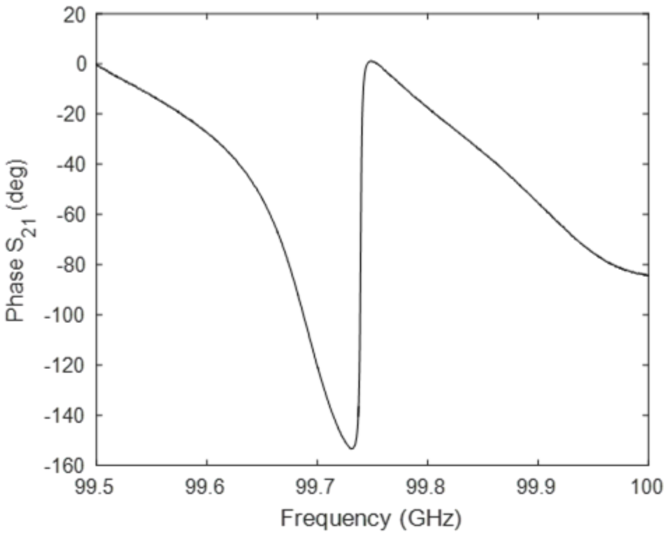

Figure 3: Measured insertion phase of the defect waveguide within the PC.

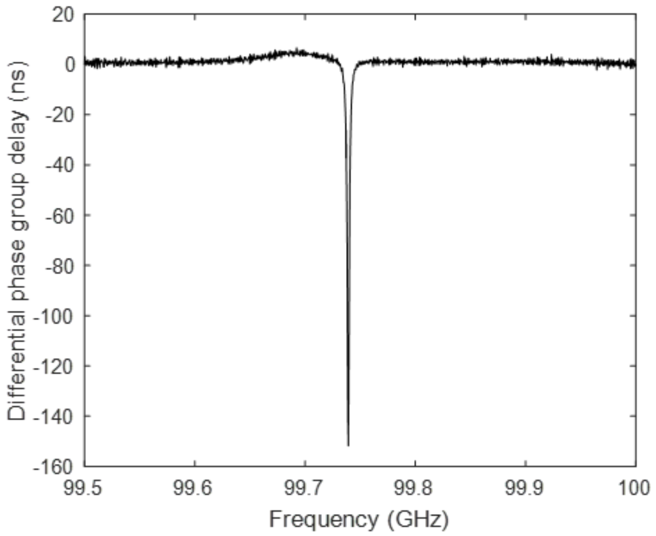

Figure 4: Measured differential-phase group delay of the defect waveguide within the PC.

IV. Conclusion

A millimetre-wave NGD network is introduced for the first time, using a photonic crystal in high-resistivity silicon. A measured group delay of -151.8 ns was achieved at a resonance frequency of 99.74 GHz, having a FoM performance that is almost double the highest previously reported value. Furthermore, it is proposed that both the group delay and frequency can be made tuneable by exploiting the inherent properties of HRS. This work demonstrates the potential for NGD-based compensation networks using a photonic crystal architecture.

Acknowledgments

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