# Photonic band gap formation by mircostrip ring

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## ABSTRACT

We show that the microstrip ring with a narrow gap exhibits a photonic band gap (PBG) that is generally believed to be created by a periodic array. The discontinuity of impedance at the narrow gap induces the multiple reflections with fixed phase correlation necessary to make the PBG. We have also discussed the tuning of the PBG frequency by applying an external voltage on a varactor mounted on the gap and the applications of this PBG ring as a tunable bandstop filter and a microwave switch.

## I. Introduction

It is well known that a periodic electronic potential due to the lattice of atoms can introduce the electronic band gap, the frequency range where electron waves are forbidden to propagate. About fifteen years ago, this well known fact was applied to control the propagation of photons [1]. It has been proved, theoretically and experimentally, that the artificial lattices of dielectric media can give rise to the frequency regions where photons cannot propagate in any direction, i.e., the photonic band gaps (PBGs) [1, 2]. Such periodic dielectric structures showing PBGs are called as photonic crystals or PBG structures. The PBG properties are scalable and thus appear in wide frequency ranges, from microwave to visible ranges [3]. There has been great interests in the application of PBG structures for microwaves and millimeter-waves. In these frequency ranges, PBG structures have been employed to improve radiation pattern of antennas [4], increase the output power of amplifiers [5], suppress higher order harmonics of resonators [6], and design new types of duplexers [7].

However, microwave circuits with PBG structures are difficult to implement in a compact physical dimension because it requires at least 5 or 6 periods of unit cells, and the physical dimension of the period is directly related to the wavelength of the center frequency of PBG. Therefore, a new microwave PBG structure with compact physical dimension would be crucial for the versatile application of microwave PBG structures. In this paper, we show that a simple microstrip ring with a narrow gap can exhibit the PBG characteristics. The physical dimension of this PBG ring is much smaller than that of the conventional microstrip PBG structures. Thus the PBG ring can overcome the size problem of conventional microstrip PBG structures. Moreover, it can be easily integrated with other microwave devices, and its stopband can be electronically tuned by incorporating a varactor in the ring.

## II. The characteristics of Microstrip PBG ring

The concept of PBG ring is based on two facts. First, microwave PBG structures can be implemented by providing a structural periodicity on the microstrip line itself without any periodic variation of dielectric constant of the substrate [8]. This is possible since the PBGs are originated from the multiple reflections with the fixed phase correlation due to the strong impedance mismatch [9]. Second, some modifications of a ring resonator can induce the multiple reflections with a fixed phase correlation. Normally, the ring resonator that consists of the feed lines, coupling gaps, and microstrip ring allows the propagation of microwave at its resonant frequencies [10]. However, the direct connection of the feed lines to the ring destroys the resonator character of the ring, since the semicircle of the ring can act as a transmission line in this case. When a small portion of the closed loop is removed further, the multiple reflections with a fixed phase correlation can be obtained due to the strong impedance mismatch at the discontinuity. Thus the microstrip ring with a narrow gap can exhibit a PBG.

The microstrip structures were fabricated on a RT/Duriod 6010 substrate, which has a dielectric constant of 10.2 and thickness of 0.635 mm covered with two copper plates, by etching one of the metal plates with conventional photolithographic method. Two 50-Ω microstrip feed lines were directly connected at both sides of the ring in order to excite the PBG ring and to detect the output. An HP 8510C network analyzer was used to measure the reflection and transmission spectra. The transmission characteristics were also studied by using a commercial electro-magnetic wave simulation program, ENSEMBLE 5.0, which is based on the method of moments (MoM). The simulation was performed on the two types of PBG ring, the circular and rectangular rings. The latter type was employed because of its easiness in the simulation.

Figure 1 shows (a) the simulated spectra of the reflected ($S_{11}$) and transmitted microwaves ($S_{21}$) through a ring resonator and (b) the measured spectra of the microstrip ring with the directly connected feed lines (to be referred to as the regular ring hereafter) when the mean diameter $2r$ and the line width $w$ are 5.1 mm and 0.5 mm, respectively. The inset in the left corner denotes the schematic of the ring. The ring resonator shows the well-known resonant transmissions at the frequencies $f_n$ given as,

$$f_n = \frac{nc}{2\pi r\sqrt{\varepsilon_{eff}}} \quad \text{or} \quad 2\pi r = n\lambda \tag{1}$$

where $n$ is a positive integer, $c$ the vacuum speed of light, $\varepsilon_{eff}$ the effective dielectric constant, and $\lambda$ is the wavelength of the microwave in the substrate. The simulation result gives the estimated value of $\varepsilon_{eff}$ 6.77. One can see that the transmission characteristics of the regular ring are quite different from those of the ring resonator. The maximum transmission occurs at the resonant frequencies of the ring resonator, but there are other ripples between resonant frequencies of the regular ring. The physical origin of later phenomena is not clearly understood at this time. We only confirmed, from the experiments and the simulation on the finite ground plane, that even simple transmission line shows this kind of ripples at the frequencies higher than 10 GHz. Anyway, it is evident that a regular ring exhibits neither resonator characteristics nor PBG characteristics.

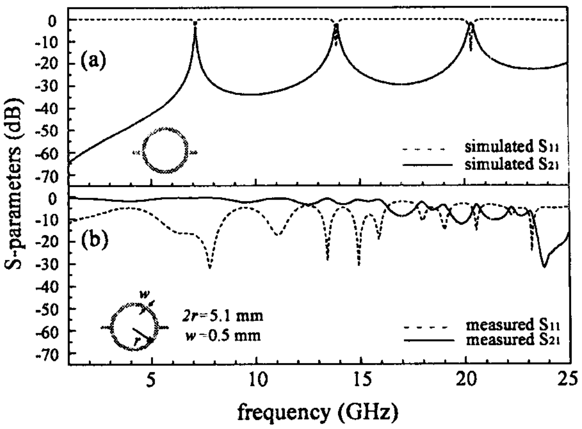

Figure 1. The transmission characteristics of (a) the ring resonator and (b) the regular ring. The inset shows the form of microstrip ring and the coupling of 50-Ω microstrip feed lines to the ring.

The measured and simulated spectra of the reflected ($S_{11}$) and transmitted microwaves ($S_{21}$) in Fig. 2 show clearly that the introduction of a small gap in the regular ring induces a strong attenuation around 6.5 GHz and 20 GHz (that correspond to $n$=1 and 3 in Eq. (1), respectively). If we define the PBG of this ring structure as the frequency range where the insertion loss is more than 20 dB, the PBG of the first attenuation extends from 5.9 GHz to 7.0 GHz. The excellent agreements between the measured and simulated results in low frequency range make sure that the appearance of the PBGs in this structure is evidently resulted from the strong impedance mismatch introduced by the narrow gap. That is, the microwave propagating along the ring should be successively reflected at the discontinuity with the fixed phase correlation when they satisfy $(2\pi r - g) = n\lambda$, and this phenomenon makes the microstrip ring with a narrow gap exhibit the PBG even if it is not a periodic array.

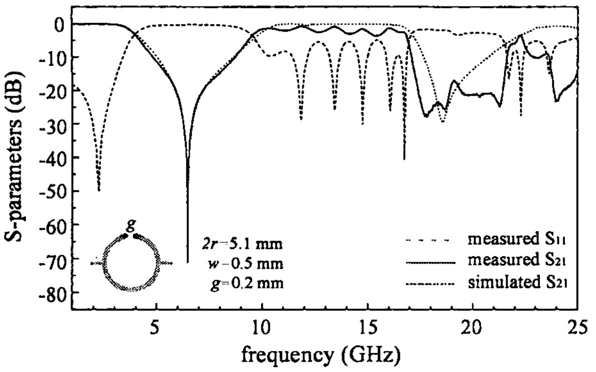

Figure 2. The reflection ($S_{11}$) and transmission ($S_{21}$) characteristics of the microstrip PBG ring with the narrow gap of $g$=0.2 mm, the ring line width of $w$ = 0.5 mm and the mean ring diameter of $2R$=5.1 mm.

The absence of the attenuation valley corresponding to second harmonic $n$=2 in Fig. 2 can be understood by considering the field configuration for the center frequency of the PBGs of the ring. The reflection condition at the gap of the ring demands the voltage (or field intensity) to be maximum at the gap boundary [10]. On the other hand, the strong reflection at the PBG frequency demands the voltage (or field intensity) to be zero at the input/output port. One can easily verify that these two conditions cannot be satisfied simultaneously for $n$=2. Thus the PBG ring can show the attenuation valley around the frequencies corresponding to the odd modes of the ring resonator. Substituting the values $2r$=5.1 mm and $\varepsilon_{eff}$ = 6.77 in Eq. (1), the odd resonant frequencies are calculated to be 7.1 GHz, 20.3 GHz, etc. The fact that these frequencies coincide well with the measured center frequencies of the PBGs of the ring confirms once again that the position of PBGs can be predicted from the odd resonance frequencies of the ring resonator. We have confirmed that this phenomenon is independent of the ring shape, i.e., circular or rectangular one.

Figure 3 shows the dependence of the simulated center frequency and the edge frequencies of the first PBG (that was arbitrarily defined as the frequency range where the insertion loss is more than 20 dB) on the mean circumference of rectangular ring $d$ when $w$=0.5 mm and $g$=0.2 mm. In the simulation, the circumference of the ring is changed by varying the lateral length keeping the longitudinal length of the rectangular ring at 5 mm. One can notice once again that the center frequency of the first PBG is in good agreements with the resonant frequency of the first mode (the dotted line designated as $f_1$), and they decreases as the circumference of the ring increases because they are inversely proportional to the circumference of the ring. Therefore we can surely control the PBG position by changing the circumference of the ring. The magnitude of PBG also decreases as $d$ increases, but the relative bandwidth of PBG, i.e., the ratio of the PBG width to the center frequency is remained nearly constant at 20%.

The reflection and transmission characteristics of a given microstrip structure can be interpreted by means of its characteristic impedance, i.e., the capacitance $C$, the resistance $R$, and the inductance $L$, of the structure. As a ring resonator can be represented by a parallel $LC$ circuit neglecting $R$, the PBG ring can also be represented by an equivalent parallel $LC$ circuit, even if the introduction of a narrow gap in the ring slightly changes the values of $C$ and $L$ from the original ones. The value of $C$ depends on the gap width $g$, the line width $w$, and the circumference $2\pi r$, while the value of $L$ depends largely on the values of $w$ and $2\pi r$. Since the characteristic impedance of the parallel $LC$ circuit becomes very large around the resonance frequency of the circuit $\omega=1/\sqrt{LC}$, the PBG ring strongly reflects the microwaves coming from the input feed line around the resonance frequency. Thus the attenuation valleys around 6.5 GHz and 20 GHz in Fig. 2, which were attributed to the frequencies where multiple reflection occurs because of the gap discontinuity, correspond to the resonance frequencies of the equivalent $LC$ circuit

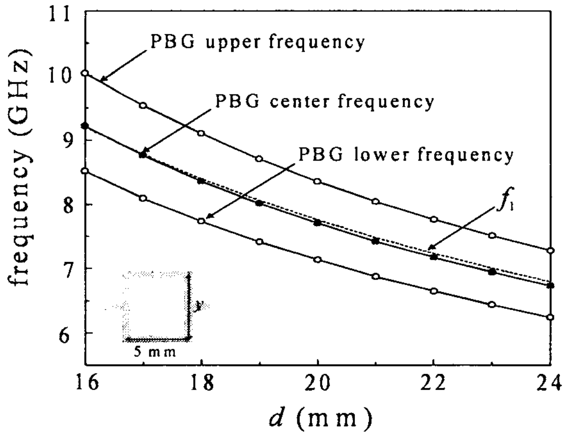

Figure 3. The dependence of the simulated center frequency and the edge frequencies of the first PBG on the mean circumference of rectangular ring $d$. The dashed line represents the first resonant mode frequency of the ring resonator having the circumference of the PBG ring.

of the ring. In this respect, one can imagine that the bandwidth of PBG would depend on the quality factor of the PBG ring. However, a close examination on the line shape in Fig. 2 reveals that the line shape is quite different from the resonance pattern with a damping especially near the base line. We believe, from our preliminary study, that the line shape near the base line is related to the impedance mismatch at the gap boundary.

Our discussion on the equivalent circuit of PBG ring suggests that the PBG can be tuned by varying the gap capacitance. This can be done by mounting a varactor diode on the narrow gap of the ring. The parallel connection of a varacter on the gap makes the varactor capacitance add up to the gap capacitance, and thus increases the total capacitance. This in turn decreases the resonant frequency of the *LC* circuit. Thus the parallel connection of a capacitor on the gap is equivalent to lengthening of the circumference of the ring as in the case of ring resonantor [10]. Because the junction capacitance of a varactor diode is voltage dependent, the stopband of the varactor-mounted PBG ring can be tuned electronically. The diffusion (depletion) capacitance dominates when a forward (reverse) bias is applied to the varactor, and it increases (decreases) with the increases of forward (reverse) bias. Thus the PBG position can be increased or decreased by a parallelly-connected varactor.

The PBG ring has some attractive features in microwave integrated-circuits. First, only few design parameters, such as the gap width and the circumference of ring, are needed. Second, the dimension of PBG ring is much smaller than that of the conventional microstrip PBG structures, and the PBG ring does not need a periodic perforation of the ground plane that is often needed for the conventional microstrip PBG structures [7-9]. Thus the PBG ring can be independently employed in the compact microwave integrated-circuits. Finally, the PBG of the ring can be electronically tuned by mounting a vatactor on the ring for the applications to tunable filters or microwave switches.

## III. Conclusion

In conclusions, we have proposed a novel microstrip ring that exhibits PBG characteristics. The stopband of the PBG ring is caused by the multiple reflection with a fixed phase correlation at the gap. This stopband is tunable by an external voltage when a varactor is connected on the gap. The small dimension of the PBG ring makes the ring practical for the applications in microwave integrated-circuits to reject unwanted frequency, and/or suppress higher order harmonics.

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