Dispersion characteristics of a slow wave structure with a modified photonic band gap*

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This paper studies the dispersion characteristics of a modified photonic band-gap slow-wave structure with an open boundary by simulation and experiment. A mode launcher with a wheel radiator and a coupling probe is presented to excite a pure TM_{01}-like mode. The cold test and simulation results show that the TM_{01}-like mode is effectively excited and no parasitic modes appear. The dispersion characteristics obtained from the cold test are in good agreement with the calculated results.

Keywords: modified photonic band-gap, slow-wave structure, TM_{01}-like mode, cold test

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1. Introduction

Photonic band-gap (PBG) structures, which are periodic lattices formed by metal or dielectric rods, are attractive for microwave and millimeter wave applications.[1,2] A PBG waveguide can be constructed when a rod or several rods are removed from the centre of PBG structures. By choosing an appropriate radius of rods, the lattice constant (the spacing between the rods) and the dimension of defect, we find that the PBG waveguide can only support the wanted modes with frequencies within a global band-gap and, therefore, provide a means for the selective suppression of unwanted modes.

Attributing the merit of mode selectivity, we can find that the PBG waveguide can alleviate and even eliminate the competition modes in microwave devices. Recently, the application of PBG structures has been extended to accelerators, backward wave oscillators and gyrotrons, etc.[3−9]

In Ref. [10], a slow-wave structure (SWS) consisting of modified PBG structures and metal plates is employed to suppress the competition modes in a Ka-band relativistic Cherenkov source. The PIC (particle-in-cell) simulation results have demonstrated that the SWS operates on in TM_{01}-like mode and has good mode selectivity. In order to study the potential applications of the device, the cold test for dispersion characteristics of the modified PBG SWS is essential. As the modified PBG SWS is an overmoded system with an open boundary in transverse, it is difficult to experimentally excite a pure TM_{01}-like mode using usual excitation techniques. In order to obtain the complete dispersion curve of a TM_{01}-like mode, a mode launcher with a wheel radiator and a coupling probe is presented in this paper. The simulation and experimental results demonstrate that the mode launcher can effectively excite the pure TM_{01}-like mode. These investigations will provide a foundation for the development of a novel and practical Cherenkov device.

This paper is organized as follows: Section 2 contains the description of the test principle. In Section 3, the excitation method is described. Simulation of the test model is presented in Section 4. The experimental procedure and results are described in Section 5. The conclusions are given in Section 6.

2. Principle of the resonant method

Figure 1 shows the physical model of the modified PBG SWS resonant cavity. In Fig. 1(a), the black dots are the position of metal rods in a normal PBG structure. When the innermost metal rods of the defect are rearranged into a circular round, a modified PBG structure is constructed. The SWS is formed by periodically placing metal plates in the longitudinal direction of the modified PBG structure. If the

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SWS of N periods ($N = 5$ in experiment) is appropriately shortened at both ends, the TM_{01}-like mode will exhibit $N + 1$ discrete resonant frequencies with phase shifts per period equally spaced between 0 and π. These resonant frequencies can be determined by testing the transmission coefficient (s_{12}) of the resonant cavity shown in Fig. 1(b) and then used to obtain the dispersion curve. The parameters of the SWS are shown in Table 1.

Table 1. Parameters of modified PBG SWS.

lattice constant (a)	3.8 mm
rod radius (b)	0.5 mm
length of the SWS period (z_0)	3 mm
thickness of the metal plate (t)	2 mm
inner radius of the metal plate ($R_{\rm in}$)	6.3 mm

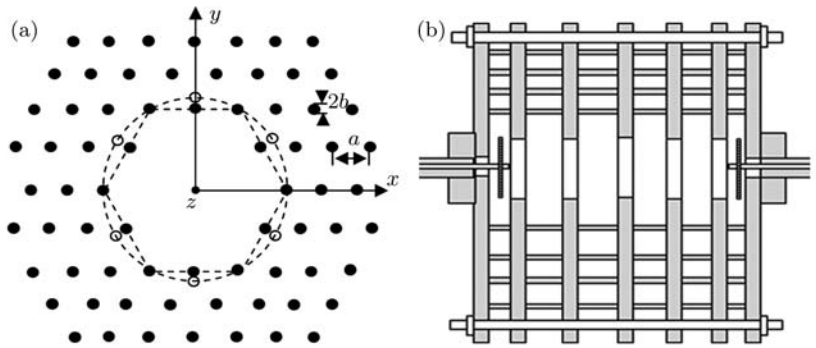


Fig. 1. Physical model of modified PBG structures and the SWS resonant cavity to test transmission coefficient. (a) Front view of modified PBG structure, (b) the SWS resonant cavity.

3. Excitation of a pure TM_{01}-like mode in the modified PBG SWS cavity

It is well known that the electromagnetic waves in any SWS include fast and slow waves, and the field concentrates on the centre for fast waves and on the surface for slow waves. Furthermore, the component of the slow wave will increase correspondingly with an increase in frequency. To learn about the characteristic of the electric field of a TM_{01}-like mode in the modified PBG SWS, with the help of high-frequency structure simulator (HFSS), we have simulated six resonant modes with phase shifts per period of 0, $\pi/5$, $2\pi/5$, $3\pi/5$, $4\pi/5$, π, which correspond respectively to 0-mode, $\pi/5$-mode, $2\pi/5$-mode, $3\pi/5$-mode, $4\pi/5$-mode and π-mode. The typically electric field patterns of the 0-mode and π-mode are shown in Fig. 2. From Fig. 2, one can note that the electric field E of the 0-mode is completely confined in the defect by metal lattices and the maximum electric field appears on the central axis. While for the π-mode, the electric field is centred on the surface of the PBG SWS and part of the electric field penetrates into the metal lattices, which will decrease the electric field intensity in the cavity and increase the difficulty of the excitation in the experiment.

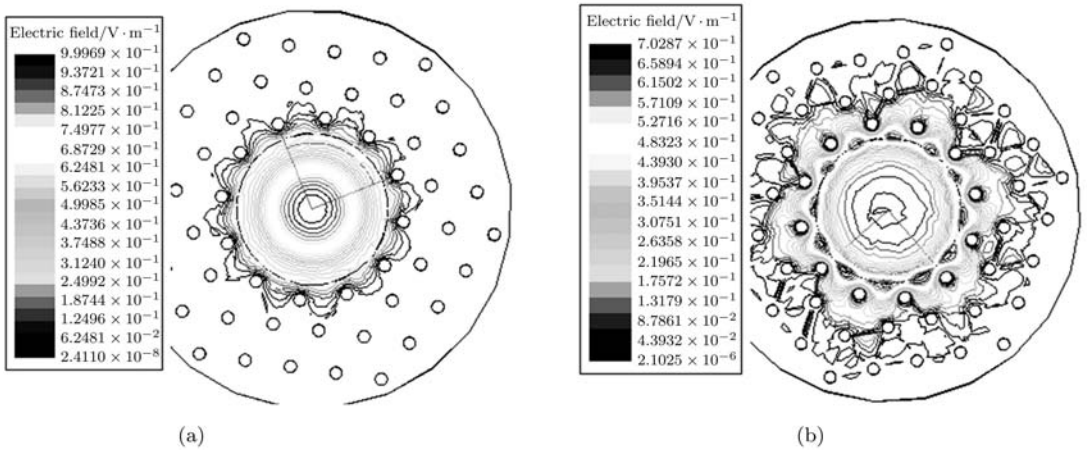


Fig. 2. The mode patterns (electric field lines) corresponding to (a) zero phase shift and (b) π phase shift of the TM_{01}-like mode in modified PBG SWS.

In order to obtain the full dispersion curve from the experiment, a suitable mode launcher for effectively exciting both fast and slow waves should be chosen. The axial coupling probe is a common excitation method, but it is difficult to excite the slow wave, especially for π-mode, because the maximum electric field does not appear in the centre. A coupling probe at the side of the PBG SWS (side coupling) can excite the slow wave but it also excites asymmetric transverse-magnetic (TM) modes and even undesired transverse-electric (TE) waves. In the modified PBG SWS, besides the TM_{01}-like mode, there are several asymmetric TM modes (such as the TM_{11}-like mode and TM_{21}-like mode), which are easier to be excited in side coupling. Therefore, the above techniques are not suitable for exciting the pure TM_{01}-like mode.

The mode launcher shown in Fig. 3 can effectively excite the fast and slow wave of the TM_{01}-like mode in the modified PBG SWS. The central probe of the coaxial line connects with the wheel radiator and stretches out of the surface of the wheel radiator. The wheel radiator is formed by many rods symmetrically arranged around a centre conductor connecting with an outer metal ring.

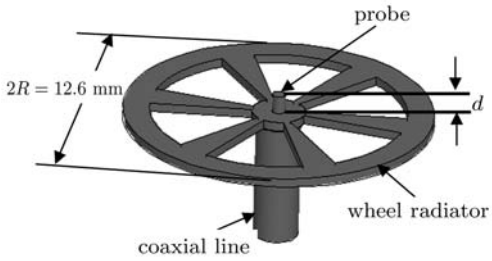


Fig. 3. Physical model of the model launcher.

The wheel radiator only excites the azimuthal component of the magnetic field H_φ, which is similar to that excited by an ideal electric dipole in direction z.[11] So the field excited by the wheel radiator can be approximated by an ideal electric dipole in z direction. Figure 4 shows the physical model of an ideal electric dipole in z direction. For the case of $\theta = 90°$, the electromagnetic fields can be denoted as follows:[12]

$$\begin{aligned} H_\phi &= \frac{I_0 h}{4\pi}\,\mathrm{e}^{\mathrm{j}kr}\left(\frac{\mathrm{j}k}{r}+\frac{1}{r^2}\right),\\ E_\theta &= \frac{I_0 h}{4\pi}\,\mathrm{e}^{-\mathrm{j}kr}\left(\frac{\mathrm{j}\omega\mu}{r}+\frac{1}{\mathrm{j}\omega\varepsilon r^3}+\frac{\eta}{r^2}\right),\\ E_r &= 0, \end{aligned} \tag{1}$$

where ε and μ are the permittivity and the permeability in vacuum, respectively, η is wave impedance, I_0 is the total current flowing through the antenna and h is the length of the antenna. Equation (1) indicates that on the surface of a plane going through the origin and perpendicular to the radiator, the excited electric field (r small) is parallel to the z axis. In the region far from the radiator, the terms of E_θ and H_φ vary as $1/r$. The Poynting vector is then completely in the radial direction, and the time-average power flow P is proportional to $\sin^2\theta$. However, E_θ is equivalent to the vector sum of E_z and E_r in the modified PBG SWS and has no significant value in the region near z axis ($\theta \simeq 0$). Therefore, it is suitable for exciting the slow-wave modes in the modified PBG SWS. For the fast wave, it can be excited by the central probe stretching out of the wheel radiator.

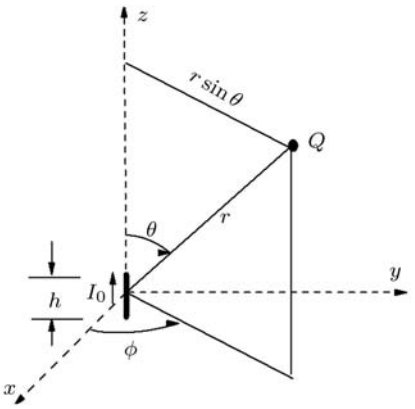


Fig. 4. The ideal electric dipole radiator.

4. Simulation results of the modified PBG SWS cavity

To study the effect of the wheel radiator and the central probe on the excitation of the slow- and fast-wave modes, we calculate the s_{12} curves of the modified PBG SWS cavity with different outer radiuses of wheel radiator (R) and the length of central probe (d) extending into the cavity. The simulated model is shown in Fig. 5. To ensure consistency with the experimental model, the boundary is set as the radiation boundary. The thickness of the radiator is 0.3 mm and the gap between the radiator and the metal plate of the SWS is 0.1 mm.

When the length of the central probe is fixed ($d = 0$ mm), the s_{12} under different radiuses of the wheel radiator is presented in Fig. 6. From Fig. 6, one can note that the π-mode is excited well with $R = 6.3$ mm. However, it will weaken with the decrease of the radius of the wheel radiator. It implies that the wheel radiator should be appropriately close to the surface of the SWS for π-mode. On the other

hand, no matter what the value of R is, the amplitudes of the 0-mode in s_{12} are always less than –10 dB.

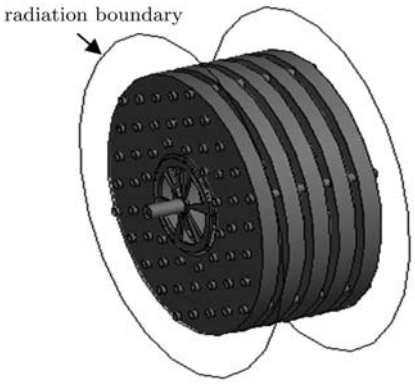


Fig. 5. Physical model for the simulation of s_{12} by HFSS code.

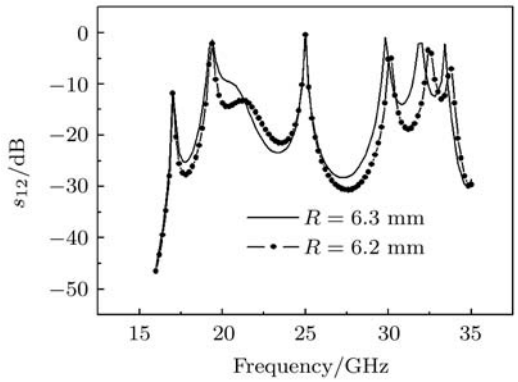


Fig. 6. The s_{12} curve dependence of radius of wheel radiator with fixed probe length.

Figure 6 also shows that the resonant frequencies with different radiuses of the wheel radiator have a shift and it is more evident at higher frequencies. According to the perturbation theory, the shift frequency affected by the mode launcher can be denoted as follows:[13]

$$\frac{\omega - \omega_0}{\omega_0} \simeq \frac{\int_{\Delta V} \left(\mu \left|\boldsymbol{H}_0\right|^2 - \varepsilon \left|\boldsymbol{E}_0\right|^2\right) \mathrm{d}v}{\int_{V_0} \left(\mu \left|\boldsymbol{H}_0\right|^2 + \varepsilon \left|\boldsymbol{E}_0\right|^2\right) \mathrm{d}v}, \qquad (2)$$

where ω_0 and ω are the resonant frequencies of the SWS cavity with and without the mode launcher, respectively, $|\boldsymbol{H}_0|$, $|\boldsymbol{E}_0|$ and V_0 are the magnetic and electric fields and volume of the SWS cavity without the mode launcher, respectively. The value of the numerator of the right fraction in Eq. (2) decides the offset of resonant frequencies. At high frequencies, the electromagnetic wave fields mainly centre on the surface of the SWS. Hence, when the mode launcher approaches the surface of the modified PBG SWS, a small change in its radius will casue a great shift of the resonant frequencies.

Figure 7 shows the effect of the central probe on s_{12} curves when the radius of the wheel radiator are fixed ($R = 6.3$ mm). As the length of central probe increases to 0.6 mm, the amplitude of the 0-mode increases to –2.6 dB. Therefore, the length of the central probe has a great effect on the excitation of fast waves.

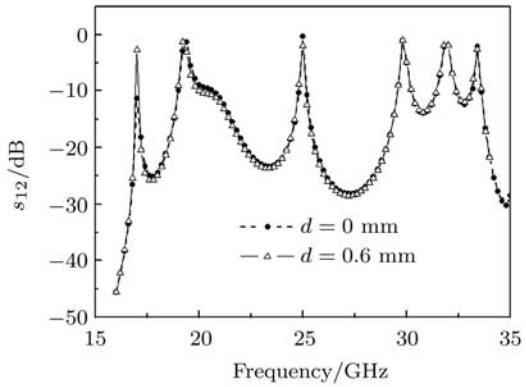


Fig. 7. The s_{12} curve dependence of the length of central probe with the wheel radiator of radius 6.3 mm.

5. Experimental results of the modified PBG SWS cavity

According to the theoretical and simulation results, we designed and fabricated an SWS cavity with 5 periods. Figure 8 shows the inner and external structures of the experimental model. The thickness of

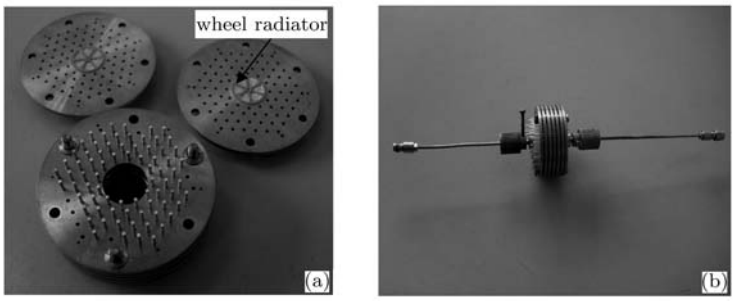


Fig. 8. Photographs of test model: (a) inner view, (b) outer view.

the radiator is 0.3 mm. To insulate the antenna from the short plate, we use a dielectric (Teflon) film with a thickness of 0.04 mm between the wheel radiator and the short plate. The gap between the radiator and the metal plate of the SWS is about 0.16 mm. The experimental results of s_{12}, which are obtained by a vector network analyser system (Agilent-8722ES), are presented in Fig. 9. The solid line and the dotted line denote $d = 0.6$ mm and $d = 0$ mm for the fixed radius of the wheel radiator ($R = 6.3$ mm), respectively. In Fig. 9, the fast-wave fields (for example 0-mode and $\pi/5$-mode) are easy to be excited with $d = 0.6$ mm.

Comparing Fig. 7 with Fig. 9, one can note that the amplitudes of the resonant modes (including 0-mode) from the s_{12} curve obtained experimentally are generally lower than those predicted from HFSS simulation. It may be attributed to two factors. One reason is the disagreement positions of the radiator in the experimental structure and simulation model. The gap between the radiator and the SWS metal plate in the experimental structure is greater than that in the simulation model. Increasing the gap will decrease the excitation of the electric field of modes in SWS. The other reason is the additional losses in the experimental structure. The radiator, short plates and rods in the experimental structure are not a perfect conductor. Furthermore, the rods are not brazed to the experimental structure, which results in imperfect electrical contact between the rods and the entire structure, additional losses are then inevitable.[14] The additional losses at higher frequencies are bigger because their electric fields completely centre on the surface of the PBG SWS and penetrate into the inner part of the metal lattices (see Fig. 2(b)). As a result, the s_{12} amplitudes at higher frequencies in experiment are aven lower than the simulation result.

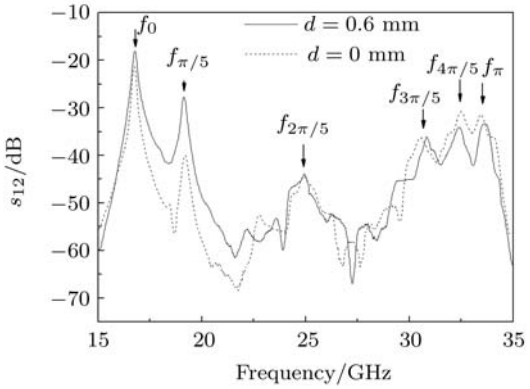


Fig. 9. The s_{12} curves obtained in the experiment.

Table 2 summarizes the measured resonant frequencies f as well as those calculated by HFSS code. The wave number k_z corresponding to each resonant frequency can be obtained from the following equation:

$$k_z = n\pi/(Nz_0), \tag{3}$$

where z_0 is the length of period, N is the number of period and $n = 0, 1, 2, 3, 4, 5$. The dispersion relation obtained from experiment is plotted as round dots in Fig. 10. It is shown that the dispersion relation obtained by experiment is in agreement with that obtained by simulation.

Table 2. Comparison between the measured and simulation resonant frequencies in the modified PBG SWS cavity.

Frequency	experiment	HFSS simulation	difference/%
f_0	16.8	17.0	1.17
$f_{\pi/5}$	19.15	19.18	0.15
$f_{2\pi/5}$	24.9	25.02	0.48
$f_{3\pi/5}$	30.4	29.9	–1.67
$f_{4\pi/5}$	32.4	31.9	–1.56
f_π	33.45	33.4	0.15

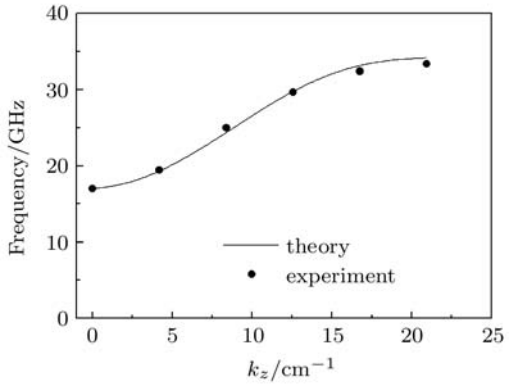


Fig. 10. Comparison of the dispersion curves obtained by experimental and calculated results.

6. Conclusion

This work studies the dispersion characteristic of a TM_{01}-like mode in a modified PBG SWS by simulation and experiment. According to the electric field distribution characteristic of the TM_{01}-like mode, a mode launcher, which is combined with a wheel radiator and a central probe, is proposed to excite a pure TM_{01}-like mode in a modified PBG SWS cavity. The simulated results show that a pure TM_{01}-like mode is completely excited by the mode launcher when the radius of the wheel radiator and the length of the probe stretching into the SWS cavity are suitable. Then, a modified PBG SWS resonant cavity with a 5-period is fabricated and tested. The dispersion curve obtained from the experiment is in good agreement with the HFSS simulation results.

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