Transmission Characteristics Of T-Typed Photonic Crystals Waveguide Based on Two-Dimensional Al2O3 Ceramic Rods Array

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Abstract. This paper proposed and validates a T-typed photonic crystals waveguide in X-band consisting of Al2O3 ceramic rods array. Based on the numerical simulations on the band gap of the photonic crystals and the function of the waveguide, the corresponding experiments are performed, which are matched well with the numerical results. The measured transmission characteristics of the photonic crystals waveguide show a wide bandwidth between 8.56 and 11.98 GHz (relative bandwidth is 34.2%). The wideband and easy integration mean that the designed photonic crystals waveguide has potential applications in the large scale integrated system and communication systems.

1. Introductions

PHOTONIC crystals (PCs) have attracted considerable attention since their abilities to control photonic motions [1,2]. Their high integration makes them be one of the promising candidates for the future integrated optical communications. Because of their unique photonic band gap (PBG) and photonic localization, PCs can be used to develop photonic crystals waveguide (PCW) for high density optical integration.

Although the PCW has received significant attention [3-6], their transmission and especially the PCW with large bandwidth have been much less studied. In our previous work, a three-port Y-shaped PCW is numerically and experimentally studied [7], but its transmission bandwidth is still narrow. Based on the PBG characteristic of the PCs, the design of PCW with wide PBG will be of great significance in academic and application fields.

In this work, we propose a T-typed PCW consisting of some square lattice Al2O3 PCs with two-line defects in the PCs. Different from the Y-typed PCW [7], the angle between the ports of the T-typed PCW is 90° or 180°, which aligns the ports of devices to be parallel or vertical. Here we focus on the T-typed PCW that is more suitable for large-scale integration systems. The proof-of-principle experiments are performed in the X-band and the experimental results are well matched with the
numerical simulations. The measured bandwidth of the PCW is 8.56GHz to 11.98GHz, while the relative bandwidth is about 34.2%. The wideband and easy integration mean our PCW has potential applications in large scale integrated system.

2. Numerical Results

2.1. Design of PCW
The designed PCW based on square lattice photonic crystals (SLPCs) is shown in Fig.1. The 11×11 SLPCs distribute in the air with two rows of line defects, whose structural parameters are presented in Fig. 1(a). The radius of the rods is \( r_0 = 0.167a \). The lattice constant is represented by \( a \).

![Fig. 1 (a) 2-D SLPCs defect structure, (b) Schematic diagram of the PCW.](image)

As shown in Fig.1(b), our PCW based on a rectangular waveguide (blue), which includes a pair of the rectangular metal waveguide to fix the 2-dimentional (2-D) (11×11) SLPCs (red). There are three ports at the centers of the three sides of PCW, which connect with the three ends of a T-shaped passage. The dielectric rod array positioned with high accuracy allows the 2-D SLPCs to guarantee the PBG characteristic. Three Flange interfaces are set at the three ports for convenience to connect with the test equipment, whose size is 22.86× 10.16 mm.

2.2. TE Mode Band Structure for PCs
Theoretically, the PBG of the PCs determines the frequency of the electromagnetic waves that can be transmitted in the PCW. We confirm the PBG by analyzing the band structure of the 11×11 SLPCs, which are formed by Al\(_2\)O\(_3\) rods (red) without any defect in Fig.2. The lattice constant of the SLPCs is \( a = 12 \) mm. The Al\(_2\)O\(_3\) rods’ radius is \( r_0 = 2 \) mm with relative permittivity \( \varepsilon_r = 9.2 \).

With above parameters of the SLPCs, its band structure is simulated by plane wave expansion method. In Fig. 3, the broad PBG is simulated only for TE modes with its normalized frequency from 0.3525 \( (2\pi c/a) \) to 0.4687 \( (2\pi c/a) \), where \( c \) is the speed of the light. When \( a = 12 \) mm, the normalized frequency region corresponds a range from 8.81 to 11.72 GHz, centered at 10.03 GHz \( (a/\lambda = 0.4016) \).
In Fig. 2, light blue area is the PBG of the PCs. The other normalized frequency from 0 to 1.2 is conduction band, in which electromagnetic waves with some frequencies may diffuse in the PCs. In principle, electromagnetic waves in the PBG frequency range are prohibited from passing through and reflected back the PCs structure. If line defects are introduced into the PCs like Fig. 1, the electromagnetic waves will be confined to stable propagation in the PCW.

2.3. Function of PCW

The transmission characteristics and function of the PCW are calculated by finite element method (FEM). The computing area includes about 53,606 grid cells, which is surrounded with scattering boundary condition (SBC). In Fig. 3, the three ports of the designed PCW are expressed as Port A, B and C. When Port A acts as the input port, the function of the designed T-typed PCW are simulated at the central frequency of 10 GHz as shown in Fig. 3(a). The numerical results show that the electromagnetic waves launched from Port A are transmitted stably to Port B and Port C in the waveguide. The power of the electromagnetic waves divided into two parts is transmitted into the two output ports. The output power of Port C is slightly larger than the power of Port B, as shown in Fig. 3(a). The transmission efficiencies of the Port A to Ports B and C are calculated at the frequency region from 7 to 13 GHz, which respectively are -4.9dB (32.4%) and -4.4dB (36.3%) at the central frequency of 10GHz, as shown in Fig. 3(b). The total transmission efficiency of the PCW is 68.7%.
Fig. 3 (a) The distribution of power in the PCW, (b) the transmission efficiencies of Port A to Ports B and C in the PCW.

When the electromagnetic waves are launched from Port B, the power of the electromagnetic waves is divided into two equal parts and transmitted into the Port A and Port C, as shown in Fig. 4(a). Because of the symmetrical characteristic of the structure, the transmission efficiencies of the Port B to Ports A and C are the same value of -4.5dB (35.5%) at 10 GHz, as shown in Fig. 4(b).

Fig. 4 (a) The distribution of power in the PCW, (b) the transmission efficiencies of Port B to Ports A and C in the PCW.

The numerical results show that the signal is transmitted stably in the T-typed PCW, and the transmission efficiencies of the PCW change smoothly within the PBG of 8.81~11.72 GHz. However, the transmission efficiencies of the PCW change sharply at the frequencies outside of the PBG. The energy spread into the PCs because there is no optical local effect.

3. Experimental Results

Before verifying the PCW, the PBG of the SLPCs has been verified by experiments in [8]. The experimental PBG is 8.62~11.55 GHz, which match well with the simulation results in section B. The isolation of SLPCs achieves -57.24 dB at 10 GHz, while the reflection efficiency of the PCs is about 90%. Obviously, the measured frequency range of the PBG shows a slight redshift for this SLPCs, which may be due to the actual dielectric constant of the Al$_2$O$_3$ ceramic posts is greater than 9.2. The testing process was introduced in [8], and is not repeated here.
The sectional view of circulator sample and the experimental setups to verify the PCW are shown in Fig.5. A precision- machined aluminum metal waveguide is used to fix the Al$_2$O$_3$ rods, as shown in Fig. 5(a). In Fig. 5(b), the two ports of network analyzer link to the port A and B of the PCW through two waveguides to coaxial converters and a pair of Sub-Miniature Version A (SMA) connectors.

In this experiment, the S parameters of the vector network analyzer describing the transmission characteristics of the tested sample can be expressed as:

\begin{align*}
S_{12} &= 10\log(P_{12}/P_2) \\
S_{21} &= 10\log(P_{21}/P_1)
\end{align*}

where $P_2$ and $P_1$ are the input power of the Port 2 and Port 1. $P_{12}$ is the transmission power from Port 2 to Port 1 of the network analyzer, while $P_{21}$ is from Port 1 to Port 2.

If the insertion loss from the connectors and electric cables is ignored, the transmission efficiency $\eta$ between two ports is tested by connecting the matched load to another port shown in Fig. 5(b), which can be expressed as follows:

\begin{equation}
10\log \eta_{BA} = S_{21} = 10\log(P_{BA}/P_1)
\end{equation}

where $P_{BA}$ is the output power of Port B from input Port A, and $\eta_{BA}$ is the transmission efficiency of Port A to Port B, whose logarithmic value is represented by parameter $S_{21}$. Similarly, $\eta_{CA}$ is the transmission efficiency of Port A to Port C.

In the scanning frequency range of 7~13 GHz, the transmission efficiencies $\eta_{BA}$ and $\eta_{CA}$ are measured with the changing frequency when signal launched from Port A. The transmission efficiency $\eta_{BA}$ or $\eta_{CA}$ has the same changing trend, as shown in Fig. 6.
Fig. 6 Measured transmission efficiencies of Port A to Ports B and C.

The transmission efficiencies inside the PBG are smooth, while it still fluctuated when outside the frequency range of the PBG. The transmission efficiency $\eta_{CA}$ of -3.99 dB (39.9%) is higher than $\eta_{BA}$ of -4.17dB (38.2%) at the frequency of 10 GHz. The total transmission efficiency of the PCW is 78.1%. Due to the symmetrical structure of the PCW, the measured transmission efficiency of Port B to A is same as Port B to C, as shown in Fig. 7. At the frequency of 10 GHz, the transmission efficiencies $\eta_{BA}$ and $\eta_{BC}$ both are -4.23dB (37.8%).

Fig. 7 Measured transmission efficiency of Port B to Port A or C.

The experimental results mean that the signal is transmitted stably in the T-typed PCW in the frequency range of 8.56 to 11.98 GHz, as shown in Fig. 6 and Fig. 7. It is obvious that the changing trend of the measured transmission efficiencies with frequency matches well with the numerical values, as shown in Fig. 3 and Fig. 4. This wide bandwidth perfectly matches with the PBG in our previous work [8].

4. Conclusion

Summarily, a more stable and easily integrated T-typed PCW with wide bandwidth is preferred for the development of large-scale integration system in addition to pursuing higher performance. PCs devices are very promising candidates due to their convenient integration in the large-scale integrated system. In this paper, a T-typed PCW with bandwidth of 3.42 GHz (the relative bandwidth is 34.2%) formed by $\text{Al}_2\text{O}_3$ rods array is theoretically and first investigated experimentally in X-band. At the central frequency of 10 GHz, the total transmission efficiency of PCW is approximately 78.1%. If some nonreciprocal sample, such as a ferrite post (sphere) biased external magnet is put in the central
point of the waveguide junction, a T-typed circulator with a 2-D PCs structure may be realized in X-band [9].

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