Crack Detection in Pipes with Different Bend Angles Based on Ultrasonic Guided Wave

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Abstract: Pipeline plays an indispensable role in process industries, because the progressing crack-like defects of in it may result in serious accidents and significant economic losses. Therefore, it is essential to detect the cracks occurred in pipelines. The axial crack-like defects in elbows with different angle are inspected by using the $T(0, 1)$ mode guided waves, in which different configurations including 45°, 90°, 135°and 180°(straight pipe) are considered respectively. Firstly, the detection sensitivity for different defect location is experimentally investigated. After that, finite element simulation is used to explore the propagation behaviors of $T(0, 1)$ mode in different bend structures. Simulation and experiment results show that the crack in different areas of the elbow can affect the detection sensitivity. It can be found that the detection sensitivity of crack in the middle area of the elbow is higher compared to the extrados and intrados of the elbow. Finally, the mode conversion is also investigated when the $T(0, 1)$ crosses the bend, and the results show that bend is a key factor to the mode conversion phenomenon which presents between the $T(0, 1)$ mode and $F(1, 2)$ mode.

Key words: axial crack-like defect; $T(0, 1)$ guided wave; different angle elbows; mode conversion

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0 Introduction

Ultrasonic guided wave is the most promising NDT techniques, which is often applied to long-distance pipeline construction health monitoring for its unique characteristics of long-range propagation, high precision and low energy attenuation. In the past years, a number of studies have been carried out to investigate the ultrasonic guided waves propagation in straight and bent pipes, especially the wave propagation beyond the elbows[1-4]. Hayashi et al.[5] proposed a semi-analytical finite element method to understand the characteristic of guided wave propagation beyond the elbows. Demma et al.[6] investigated the transmission and reflection behavior of guided waves propagation and the elbow joints were mainly discussed. Furthermore, Lowe et al.[7] studied the defection detection sensitivity through the built relationship between the defect size and the strength of reflection echo. Liu et al.[8] used $T(0,1)$ guided wave to detect longitudinal and circumferential defects and the results indicated that the longitudinal defect showed a higher detection sensitivity for the $T(0,1)$ guided wave with circumferential propagation characteristics. Relevant works have also been performed to study mode conversion behavior of guided waves[9-12]. Research conducted by Verma et al.[13] revealed that the axisymmetric $L(0, 2)$ mode is converted into other possible non-axisymmetric modes while travelling across the bend. Recently, three different pipe configurations were discussed to investigate the guided waves propagation behaviors of $L(0,2)$ mode[14]. Simulation and experiment results showed that the pipe configurations have no effect on propagation characteristics when guided

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waves crossed the first bend instead of the second one. The axial crack-like defects in different areas of 90°elbow were studied by Qi et al[15]. and the results indicated that the defect in middle area of the elbow presented the highest detection sensitivity.

Previous studies have achieved fruitful results. However, different configurations, including 45°, 90°, 135°and 180° (straight pipe), often need to be considered in practical engineering applications, and crack-like defects will occur at different parts of the elbow. Thus, it is necessary to detect the defections in different areas with different angle elbows. In order to further investigate those problems, we focus on the detection sensitivity investigation of axial crack-like defects in the intrados, the extrados and middle of various elbows and mode conversion during the propagating process. Firstly, the methods of crack detection are introduced. Then, the optimum excitation frequency is selected by the penetration rate of guided waves. After that, the detection sensitivity for different defect location with different angle elbows is experimentally investigated, and the finite element simulation is carried out in order to validate the experimental results. Finally, the mode conversion behaviors are explored when the guided waves pass through the elbow.

1 Simulation and Experiment

1.1 Finite element simulation

Three-dimensional finite element model is used for modeling the propagation of $T(0,1)$ mode across bends of different angles. In order to simplify the complex boundary conditions, this simulation is implemented at both ends of hinge support under vacuum pipe. At the same time, the instantaneous displacement load is only applied to the nodes at one end of the pipe, which can not only reduce the computational simulation time but also ensure the accuracy of the calculated results. The mesh followed the theory that the length of grid should be less than 1/8 guided wavelength[16]. The circumferential direction is divided into 32 elements and 5 mm long element along the axial direction is selected, while elements in the bend part are refined to acquire more accurate results. Then part of the elements which are defined as defect does not participate in the calculation. The $T(0,1)$ mode is excited by loading an identical torsion force in circumferential direction at the 32 points at one end of the pipe, and a 10-cycle sinusoidal signal modulated by Hanning windowed is used for excitation. The total calculate time and iteration step are 1.6×10^{-3} and 1×10^{-7} s, respectively, based on $T> 2l/\min(V_g)$ and $\triangle t< 0.8\times L_E/\min(V_g)$[17], where l is the length of pipe, L_E the size of element, V_g the group velocity. The material mechanical parameters of steel pipe are modulus of density $\rho=7.932$ kg/m^3, the elastic modulus $E = 211$ GPa and Poisson′s ratio $v=0.28$.

1.2 Experimental setup

Experiments are carried out to validate the finite element results. The steel pipes with outer diameter of 76 mm, inner diameter of 65 mm, pipe length of 2 m, and elbow curvature of 100 mm are used in the experiments. At the same time, the pipes are bent with the angles of 45°, 90°, 135° and 180° (straight pipe). The crack-like defects are artificially manufactured in intrados, extrados and middle of an elbow with 30 mm length and 1 mm width. Multi-chip sensor excitation and one sensor reception are used to improve the reliability of the detection. In order to suppress non-axisymmetric modes and excite more axisymmetric mode, 16 shear mode piezoelectric elements (size of 15 mm × 7 mm × 4 mm) are pasted on each end of the pipe evenly, which excites symmetry torsional mode along the circumferential direction, as shown in Fig. 1.

The experiment system shows in Fig. 2 consists of a waveform generator (Tektronix AFG3021C), a digital oscilloscope (Tektronix DPO 2012B), a power amplifier (AG 1006), a computer, pipes and piezoelectric elements. A 10-cycle sinusoidal signal is generated by the waveform generator and amplified by the power amplifier, which excites the 16 piezoelectric elements

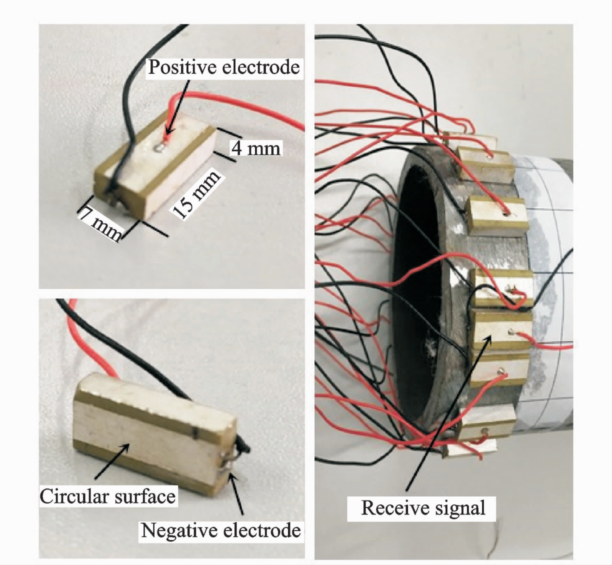


Fig. 1 Location of piezoelectric transducers

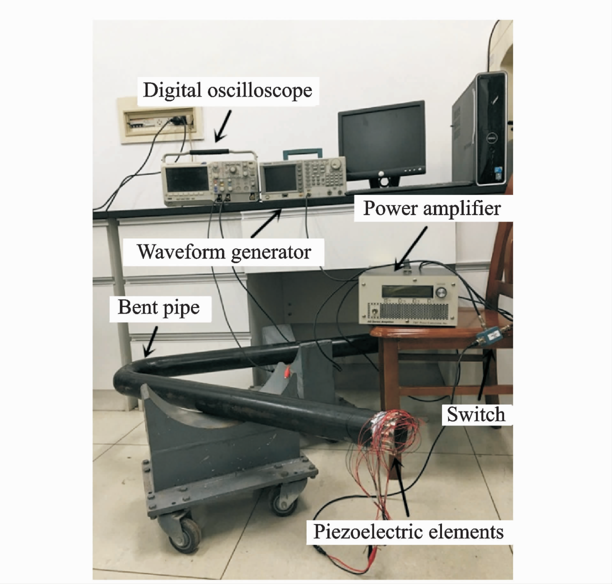
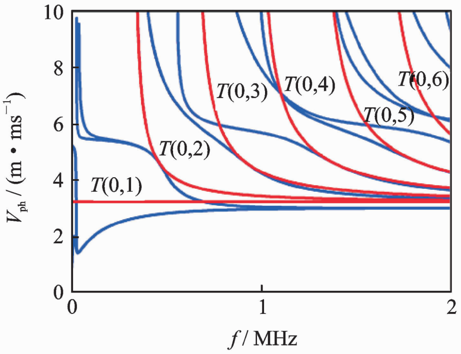


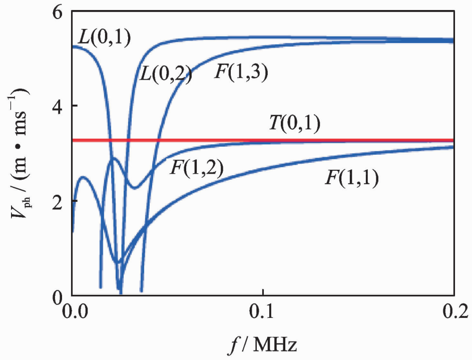
Fig. 2 The experiment system

in parallel and a single element to receive the return signal after a four-meter guided waves propagation.

After that, the commercial software DISPERSE is used for dispersion curve calculation when guide waves propagate in pipes. Fig. 3 shows the dispersion curves for the pipes with outer diameter of 76 mm and inner diameter of 66 mm. Fig. 3(a) is the phase velocity dispersion curves range 0—3 MHz and Fig. 3(b) the group velocity dispersion curves range 0—0. 2 MHz, which show that $T(0,1)$ mode is the only non-dispersion in the frequency range 0—0. 2 MHz, with a stable group velocity of 3 260 m/s. Moreover, $T(0,1)$ has a circumferential vibration modal characteristic, therefore it is the optimum mode to detect axial defects compared with other modes.



(a) Dispersion of phase velocity



(b) Dispersion of group velocity

Fig. 3 Dispersion in frequencies of 0—200 kHz

2 Results and Discussion

2. 1 Detection sensitivity of defects in different areas with different bend angles

Guided waves energy is related to the excitation frequency, the higher the excitation frequency, the more guided waves energy. However, the guided waves modes will be increased with the increase of excitation frequency. Therefore, it is essential to select an appropriate wave mode and frequency range to ensure detection sensitivity. The experimental results indicate that $T(0,1)$ mode can be excited well in a range 32—52 kHz. Fig. 4 shows the ratio of the echoes amplitude to excitation amplitude in integrated pipes with various bend angles from 32 to 52 kHz.

From Fig. 4, it can be seen that guided waves can propagate along the whole pipe in the frequency range. However, after a 4 m long propa-

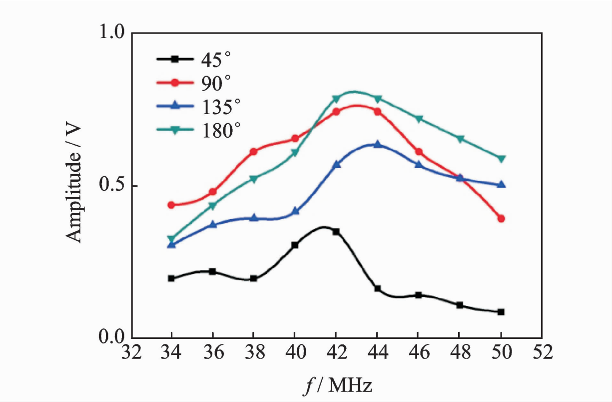
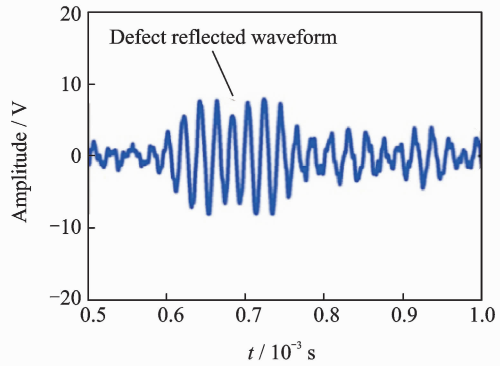


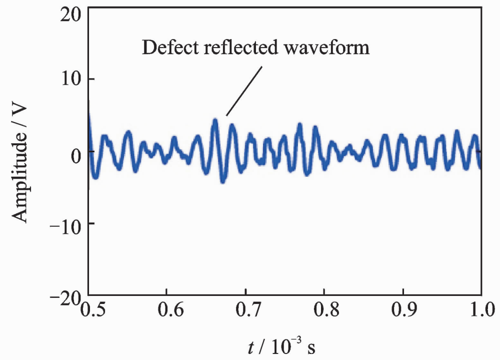
Fig. 4 Ratio of the echoes amplitude to excitation amplitude in integrated pipes

gation, guided waves experience a large attenuation which can be revealed through the amplitudes of the end echoes. It can also be observed that guided waves in pipe with 45° angle experience larger energy attenuation than those in straight pipe does, which demonstrates that different bend structure affects propagation of guided wave. The smaller angle results in more energy attenuation. Under the same angle, the amplitudes are larger from 42—44 kHz which means that energy attenuates less in this frequency range. Thus 42 kHz is selected to conduct the following experiments to ensure the detection sensitivity.

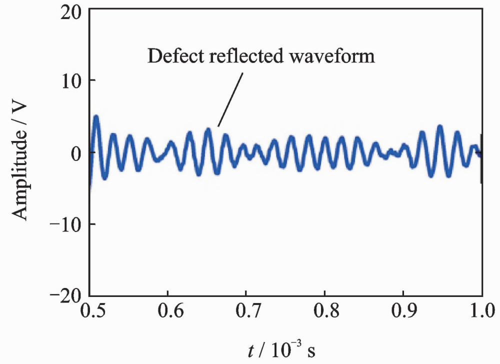
Figs. 5—7 show the received time domain waveform when cracks exist in different areas in pipes with different bend structures. Figs. 5(a—c) are the waveforms when cracks exist in extrados, intrados and the middle side area in pipes with 45° bend, respectively. From Fig. 5(a), a waveform exists at the time of 0.6 ms that can be calculated to be the defect waveform according to the dispersion curves and defect position, which is in accordance with the experiments. Amplitudes of defect waveforms in Fig. 5(a) are larger than those in Figs. 5 (b,c). Defect in intrados can be hardly distinguished because of the small amplitude. The results indicate that defects in the middle side area of the bend are the easiest to be detected, while defects in intrados are the most difficult to be detected, which means that detection sensitivity is the highest in the middle side area of the bend. From Figs. 6—7, some similar results can be acquired for pipes with 90°and 135° bends, which shows that detection sensitivity is related to the location in the bend instead of the bend structure. Then the elbow defects are detected under different excitation frequencies, the results show detection sensitivity is the highest in the middle side area of the bend under the arbitrary excitation frequency.



(a) Crack in middle side area



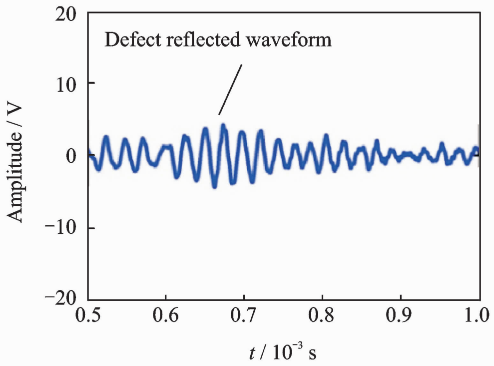
(b) Crack in extrados



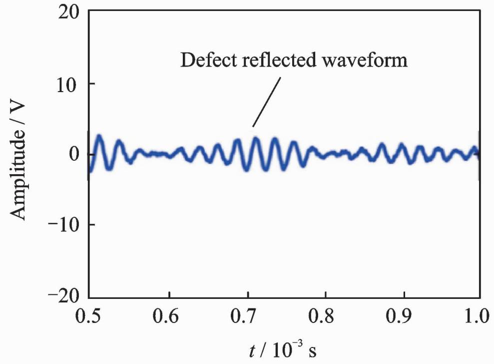
(c) Crack in intrados

Fig. 5 Received time domain waveform signals in 45° bent pipe

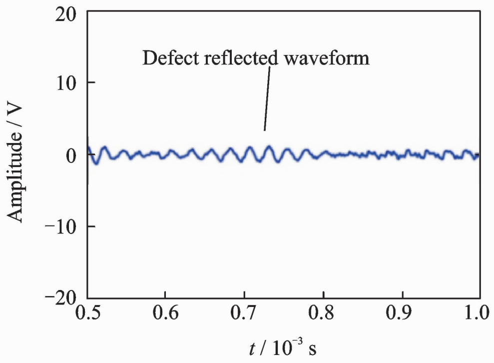
The experimental results based on time-domain waveform are highly consistent with the simulations which explain the results from the en-



(a) Crack in middle side area

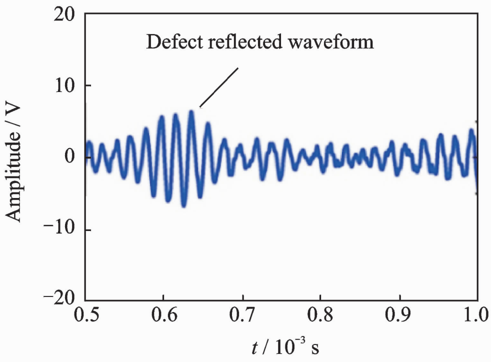


(b) Crack in extrados

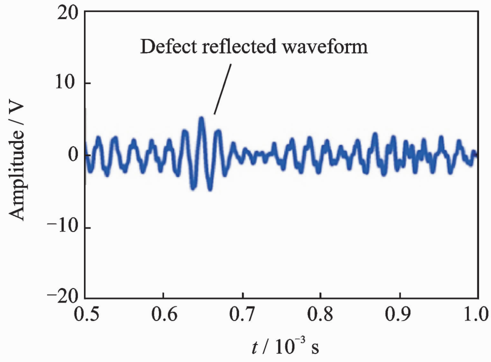


(c) Crack in intrados

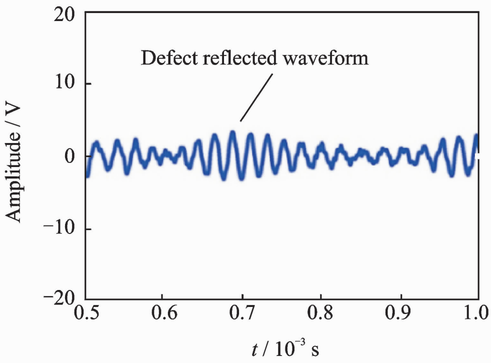
Fig. 6 Received time domain waveform signals in 90° bent pipe



(a) Crack in middle side area



(b) Crack in extrados



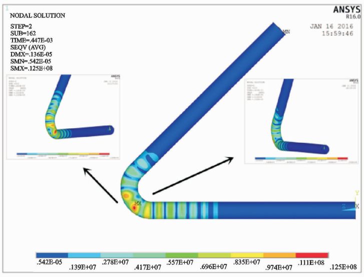
(c) Crack in intrados

Fig. 7 Received time domain waveform signals in 135° bent pipe

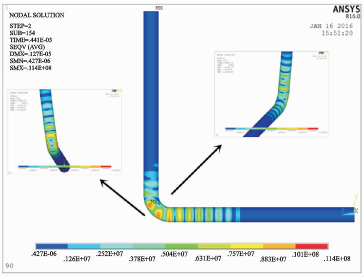
ergy focusing as shown in Fig. 8. Although the pipe configurations are different, the energy of the guided waves tends to focus on one side of the elbow when the guided waves travel across the elbow. It can be concluded that the different configurations have no influence on the energy focus. The energy will focus on extrados and is far away from the intrados.

2.2 Mode conversion in elbow

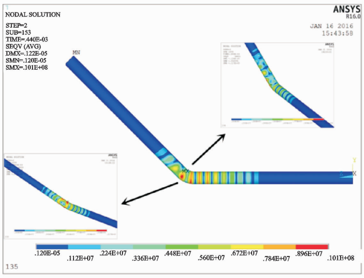
As shown in Figs. 5—7, it is found that the defect signal is often disturbed by the noise signal because of the mode conversion, so it is necessary to study the mode conversion. Fig. 9 shows the snapshot of the transient stress distribution. From Fig. 9(a), $T(0,1)$ mode propagates along the pipe symmetrically and no other mode exists during the whole propagation. However, in Fig. 9 (b), when $T(0, 1)$ mode travels across the bend, the symmetrical mode is converted into other asymmetrical modes. Bend is a key factor to the mode conversion phenomenon because bend is an asymmetrical structure.



(a) 45° bent pipe

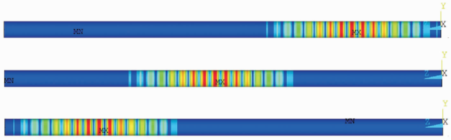


(b) 90° bent pipe

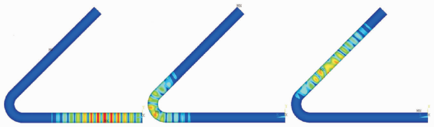


(c) 135° bent pipe

Fig. 8 Snapshot of transient stress distribution in the elbow



(a) Transient stress distribution in straight pipe



(b) Transient stress distribution in bent pipe

Fig. 9 Snapshot of the transient stress distribution

As shown in Fig. 10, multiple frequencies signal aliasing together causes it difficult to identify the signal pattern when the time-domain signal is relatively weak. Instead, it can be observed the signal of a single frequency component with the change of time through the short-time Fourier transform (STFT) easily. Group velocity dispersion curves describe the relationship between the group velocity and frequency, which can be transformed into time-frequency curves when the propagation distance is confirmed. We investigate the mode conversion occurring in elbow, therefore the guided waves propagation distance is 2 m. Then the received time-domain signals can be converted into the time-frequency-energy distribution through the method of STFT, the two time-frequency graphs mentioned above are combined as Fig. 11 shows.

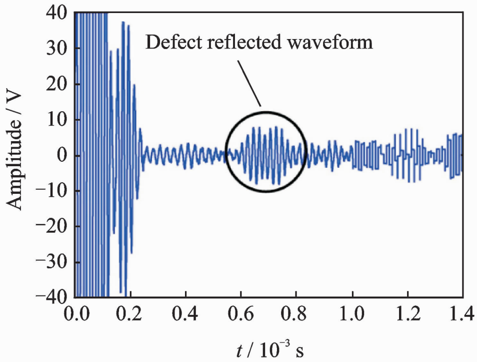


Fig. 10 The received time domain waveform signals of the 45°bent pipe

As shown in Fig. 11, the time-domain wave packet is clearly distinguished in time-frequency domain. Two overlapping time domain wave packet is a combination of $T(0,1)$ component and $F(1,2)$ component at the frequency ranging from 30 kHz to 70 kHz. This result indicates that most of $T(0,1)$ mode converts into $F(1,2)$ mode after passing through the elbow. Consequently, the STFT method can analyze the guided waves mode conversions in the dissemination

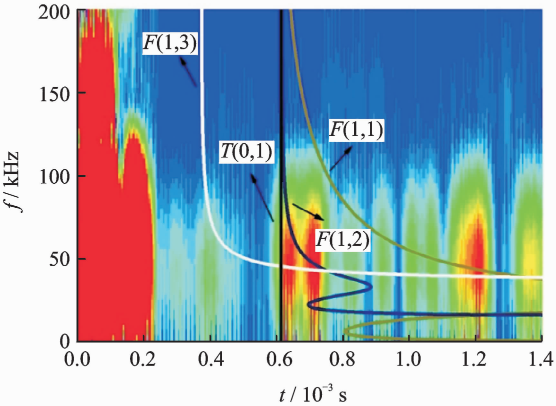


Fig. 11 Results of time-frequency analysis

process.

3 Conclusions

The effect of pipe bend angles on guided waves propagation based defect detection is investigated by experiment and simulation method. Simulations and experiments are conducted to investigate the detection sensitivity for different crack location and mode conversion in the bend, with conclusions as follows:

(1)The results reveal that the guided waves energy will be attenuated when the guided waves travel across the elbows, and the largest attenuation occurred in 45° bent pipe.

(2)Defect location in the bend affects the detection sensibility. Experiment results indicate that the middle side area of the bend exhibits the highest detection sensitivity. The simulation results confirm this from the distribution of energy.

(3)Simulation results reveal that more mode conversion can be found when bend angles are smaller. $T(0,1)$ mode will convert to $F(1,2)$ when guided waves travel across the bend.

Acknowledgments

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