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Cylindrical Unidirectional Wave Transmission and Experiments Based on UWB-SWPL

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Abstract. Current studies have found that electromagnetic waves propagate in both positive and negative directions on the surface of magneto-optical media, and even have unidirectional propagation characteristics. This unique physical phenomenon has attracted the attention of many scholars in the industry. Through the derivation and theoretical analysis of vector potential equation, scalar wave equation and dielectric wrapped conductor waveguide, the existing TM mode and TE mode are shown. Then the millimeter wave energy is effectively radiated by the horn antenna to achieve a high efficiency coupling device. The electromagnetic energy is gathered on the surface of the conductor and transmitted along the conductor. At last, the validation of surface wave transmission is realized through experiments, which proves its authenticity.

1. Introduction

At present, there are two methods to realize this kind of one-way electromagnetic surface wave. One is that Haldane and Raghu analogize the surface modes of quantum Hall effect in non-reciprocal photonic crystals to obtain this one-way effect [1]. The other is to realize the one-way effect by using the asymmetric dispersion relation of the mode of electromagnetic wave on the surface of magneto-optical medium or rotating magnetic medium.

Photonic crystal is a periodic medium which controls the propagation of electromagnetic wave in photonic forbidden band. In periodic medium, the description of photonic crystal is similar to that of electron wave in crystal, and can also be described by photonic band structure. Band gaps can also occur between photonic bands, i.e. gaps between them, but the light in the band gaps can not be transmitted in photonic crystals. In the forbidden band frequency range, the propagation of light wave can be controlled by introducing a specific defect.

Scholars have further studied unidirectional propagation [3], tunable power divider [4], broadband annulus [5], multimode unidirectional waveguide [6], which is composed of unidirectional waveguide, unidirectional coupling. In addition, the ferrite is used to realize the unidirectional propagation of electromagnetic waves on different structures of gyromagnetic photonic crystals. Slow waves in unidirectional waveguides are studied, and multi-mode unidirectional waveguides with Dachen's size are verified by experiments.

Unidirectional waves can also be realized based on the asymmetric dispersion relation of surface modes of electromagnetic waves on magneto-optic or rotating magnetic media. This asymmetric dispersion relation refers to the different interaction between left-handed and right-handed swirling waves in non-reciprocal media. When the two interactions are very different in a particular frequency band, there may be only one polarization mode. Mathematically, the asymmetric dispersion relation is derived from the asymmetric characteristic equation of surface modes with relative propagation constants. In a particular frequency band, the dispersion relation can have a single group velocity direction. In addition, there are also different methods to obtain such unidirectional surface waves, such as surface plasma in magnetic field, interface between two magnetic domains with reverse magnetic field [7], and waveguide composed of metal-dielectric-gyromagnetic medium [8]. Compared with the way of realizing unidirectional wave in photonic crystal, this way is easy to understand and can be realized through thin film material without periodic structure. However, there are many theoretical and experimental studies in this field. In this paper, through theoretical analysis, calculation and numerical simulation, a simple radiation and coupling device is designed to verify the transmission of surface wave.

2. Summary of Surface Wave Transmission

2.1. Vector Potential Equation and Scalar Wave Equation

2.1.1. Vector potential equation

According to the Maxwell equations in complex frequency domain, the following results are obtained:

$$\begin{cases} \nabla\times\overline{E} = -j\omega u\overline{H} \\ \nabla\times\overline{H} = j\omega\varepsilon\overline{E} \\ \nabla\bullet\overline{E} = 0 \\ \nabla\bullet\overline{H} = 0 \end{cases} \tag{1}$$

In the above formula, the right current source and charge source of the equation system are 0, because the analyzed region is passive (requiring that the medium characteristics are linear, isotropic and uniform, so operator ∇ can be independent of (ε,μ,σ)).

From the above formula, the vector potential equation of the passive region of the electromagnetic field is shown as follows, where $k^2=\omega^2\varepsilon\mu$.

$$\nabla^2\overline{A}+k^2\overline{A}=0 \tag{2}$$

$$\nabla^2\overline{F}+k^2\overline{F}=0 \tag{3}$$

The solution of electromagnetic field in accordance with Maxwell equation (1) can be expressed as:

$$\overline{E} = -\nabla\times\overline{F} - j\omega\mu\overline{A} + \frac{1}{j\omega\varepsilon}\nabla(\nabla\bullet\overline{A}) \tag{4}$$

$$\overline{H} = \nabla\times\overline{A} - j\omega\varepsilon\overline{F} + \frac{1}{j\omega\mu}\nabla(\nabla\bullet\overline{F}) \tag{5}$$

Different from the corresponding sources $\overline{J}$ and $\overline{M}$ of $\overline{A}$ and $\overline{F}$, $\overline{A}$ and $\overline{F}$ are understood as the universal sources corresponding to electric field intensity and magnetic induction intensity. According to the superposition theorem of electromagnetic field, the solution of analytical region can be superposed by the solution of single source $\overline{A}$ and the solution of single source $\overline{F}$.

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$$\begin{cases}\overline{E} = -j\omega\mu\overline{A} + \dfrac{1}{j\omega\varepsilon}\nabla(\nabla \bullet \overline{A}) \\ \overline{H} = \nabla \times \overline{A}\end{cases} \tag{6}$$

$$\begin{cases}\overline{H} = -j\omega\varepsilon\overline{F} + \dfrac{1}{j\omega\mu}\nabla(\nabla \bullet \overline{F}) \\ \overline{E} = -\nabla \times \overline{F}\end{cases} \tag{7}$$

Formulas (13) and (14) are generally applicable to passive and linear media. In the case of attenuated media, only the corresponding media constants need to be replaced by complex numbers. Such as: $\varepsilon = \varepsilon^{'} - j\varepsilon^{''}, \mu = \mu^{'} - j\mu^{''}$.

Based on $\overline{A}$ and $\overline{F}$ sources, there are two special cases as follows:

$$\overline{A} = \hat{e}_z\psi, \overline{F} = 0 \tag{8}$$

$$\overline{A} = 0, \ \overline{F} = \hat{e}_z\psi \tag{9}$$

These two cases correspond to TM mode and TE mode respectively. Formula (8) shows that only $\overline{A}$ is not zero. Because of $\overline{H} = \nabla \times \overline{A}$, the magnetic field is perpendicular to A. From formula (9), only $\overline{F}$ is not zero. Because of $\overline{E} = -\nabla \times \overline{F}$, the electric field and F are perpendicular to each other. By substituting formulas (8) and (9) into formulas (7) and (8), the solutions of electromagnetic fields in TM mode and TE mode can be obtained.

Formulas $\nabla^2\overline{A} + k^2\overline{A} = 0$ and $\nabla^2\overline{F} + k^2\overline{F} = 0$ can be further solved in Cartesian coordinates, and the Helmholtz equation is satisfied in each direction.

$$\nabla^2\psi + k^2\psi = 0 \tag{10}$$

Therefore, for the case of formula (8) above, it is only necessary to find ψ in the Z direction based on formula (10); the same is true for formula (9).

In passive, linear and uniform media, the electromagnetic field can be obtained by superposition of TM mode field and TE mode field. Because by properly choosing ψ, corresponding TM and TE can be constructed, such as: $\dfrac{\partial^2\psi^f}{\partial z^2} + k^2\psi^f = jw\varepsilon H_z$.

2.1.2. Solutions of helmholtz equation

The boundary and interface of the region studied in this paper have regular shape. After choosing the appropriate coordinate system, the equation can be simplified by the method of separating variables. Therefore, the cylindrical coordinate system should be chosen to simplify the description of boundary conditions, that is, the boundary conditions are expressed by simple functions. According to Laplacian operator: ∇^2, the concrete expression in cylindrical coordinate system is as follows:

$$\nabla^2\psi = \frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\frac{\partial\psi}{\partial\rho}) + \frac{1}{\rho^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\psi}{\partial z^2} \tag{11}$$

$$\psi = R(\rho)\Phi(\phi)Z(z) \tag{12}$$

The Helmholtz equation is substituted and sorted out:

IOP Conf. Series: Materials Science and Engineering **719** (2020) 012052 doi:10.1088/1757-899X/719/1/012052

$$\frac{1}{\rho R}\frac{\partial}{\partial \rho}(\rho\frac{\partial R}{\partial \rho})+\frac{1}{\rho^2\Phi}\frac{\partial^2\Phi}{\partial\phi^2}+\frac{1}{Z}\frac{\partial^2 Z}{\partial z^2}+k^2=0 \tag{13}$$

The general solution of the equation can be expressed as:

$$\psi=\sum_n\sum_{k_z}C_{n,k_z}\psi_{k_\rho,n,k_z}=\sum_n\sum_{k_z}C_{n,k_z}B_n(k_\rho\rho)h(n\phi)h(k_z z) \tag{14}$$

According to the boundary conditions of the solved region, the appropriate expression of the solution is selected. Then k_ρ, n, k_z is determined according to the boundary value. The constant C_{n,k_z} is determined by the source in the region. $\psi_{k_\rho,n,k_z}=B_n(k_\rho\rho)h(n\phi)h(k_z z)$ is the fundamental solution of the equation.

2.1.3. Dielectric wrapped conductor waveguide theory
The model of the dielectric wrapped conductor is shown in the following figure:

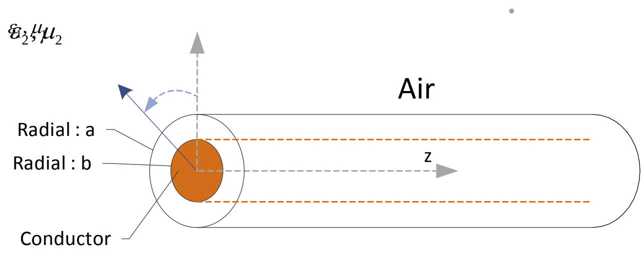

Figure 1. Diagram of dielectric wrapped conductor waveguide.

The inner layer is a conductor with a radius of b, which acts as an ideal conductor in the calculation below; the outer layer is a dielectric layer-region 1 with a radius of a and its dielectric constant is ε_1, μ_1; the outer layer is air-region 2, where the dielectric constant ε_2, μ_2 is used. TM and TE modes are analyzed respectively.

Because the innermost layer is an ideal conductor, its internal electromagnetic field is 0. Only 1/2 of the region needs to be analyzed. The basic solution of Helmholtz equation is chosen in the case of region 1:

$$\psi^{m1}=AB_n^{m1}(k_{\rho1}\rho)\cos(n\phi)e^{-jk_z z} \quad \text{(15) TM Mode}$$

$$\psi^{e1}=BB_n^{e1}(k_{\rho1}\rho)\sin(n\phi)e^{-jk_z z} \quad \text{(16) TE Mode}$$

In the case of Region 2:

$$\psi^{m2}=CB_n^{m2}(k_{\rho2}\rho)\cos(n\phi)e^{-jk_z z} \quad \text{(17) TM Mode}$$

$$\psi^{e2}=DB_n^{e2}(k_{\rho2}\rho)\sin(n\phi)e^{-jk_z z} \quad \text{(18) TE Mode}$$

Among them:

$$k_z^2+k_{\rho1}^2=k_1^2=\omega^2\varepsilon_1\mu_1 \tag{19}$$

$$k_z^2+k_{\rho2}^2=k_2^2=\omega^2\varepsilon_2\mu_2 \tag{20}$$

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3. Design of Coupling Device and Dielectric Lens

3.1. Coupling Device

At present, the key technology to be tackled is the coupling device. Coupling devices are divided into tight-binding coupling device and extraction coupling device. Firstly, the tight-binding coupling device is designed and simulated in this paper.

According to the theory of electromagnetic binding, if the binding effect is to be formed in the corresponding region, the reactance boundary conditions need to be formed in this region. There are two ways: the boundary between two different dielectric constant media and the boundary between conductors.

The electromagnetic energy is bound to the power line, and the power line has a dielectric layer, which belongs to the coexistence of the conductor boundary and the dielectric boundary. However, when the incident angle of the electromagnetic wave is at a certain angle with the conductor, it is approximately mirror reflection at the boundary of the conductor; at this time, most of the energy will be reflected out.

3.2. Coupling Device

3.2.1. Design scheme

First of all, the dielectric lens is discussed, and the implementation framework is designed. The design scheme is as follows.

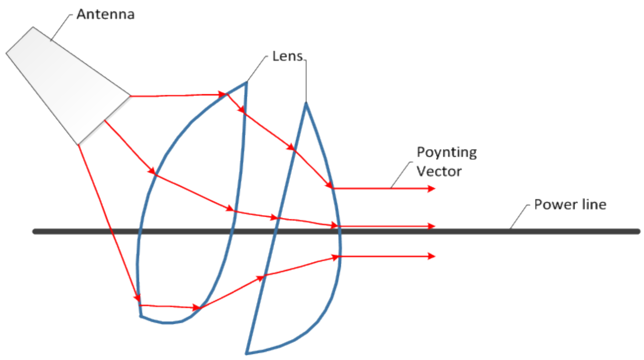

Figure 2. Working schematic diagram of lens aggregation.

The energy transmission path is shown in the red line above. A series of lenses (possibly a combination of lenses) are used to change the transmission path of the wave, eventually gathering the energy around the power line and forming a surface wave propagating along the line.

3.2.2. Lens shape selection

From the analysis of the horn antenna in front, it can be seen that after leaving the antenna aperture, the electromagnetic waveform forms a spherical wavefront, but gathers in a solid angle, and diffuses with the distance from the antenna aperture. Therefore, the incident wave of a lens can be seen as a wave propagating outward from a certain point to a certain solid angle. But using point source in simulation will not affect the result analysis.

4. Experimental Analysis

4.1. Experimental Principle

Power Line is illuminated directly by rectangular waveguide (simulated by metal rod). For the Power Line region, that is, the area between two rectangular waveguides, it is only the space area of the Power Line. After electromagnetic shielding around the waveguide, the electromagnetic field mode can not be leaked into space. Because the working frequency band is located in millimeter wave, the energy radiated from waveguide to space is concentrated in the range of its rays, so the direction of TX and RX ends is staggered, which will greatly avoid electromagnetic energy conducting RX ends directly from TX ends in the air. The signals received at the RX end can only arrive along the Power Line. According to the theoretical analysis of the above dielectric wrapped conductor, the electromagnetic energy transmitted must conform to the solution of Maxwell equation system in the area outside Coupling Cavity - the situation that dielectric wrapped conductor exists in passive, linear and uniform area, that is, the electromagnetic field forms the transmission effect of surface wave along the power line.

4.2. Experimental Result

Table 1. Test result.

Connection state	Receiving power	Attenuation	Transmission attenuation	picture	Remarks
Direct connection	-22.16	22.16	0	5,6	1.419GHz
diagonally	-87.57	87.57	65.41	7,8	1.3GHz
diagonally+PCB board+medium	-69.62	69.62	47.46	9,10	1.3GHz
horn diagonally+Metal mesh	-88.45	88.45	66.29	11,12	1.3GHz
horn diagonally+Metal mesh+PCB board+medium	-93.07	93.07	70.91	13,14	1.3GHz
horn diagonally+Metal mesh+Aluminum tube+medium	-100.98	100.98	78.82	15,16	1.3GHz

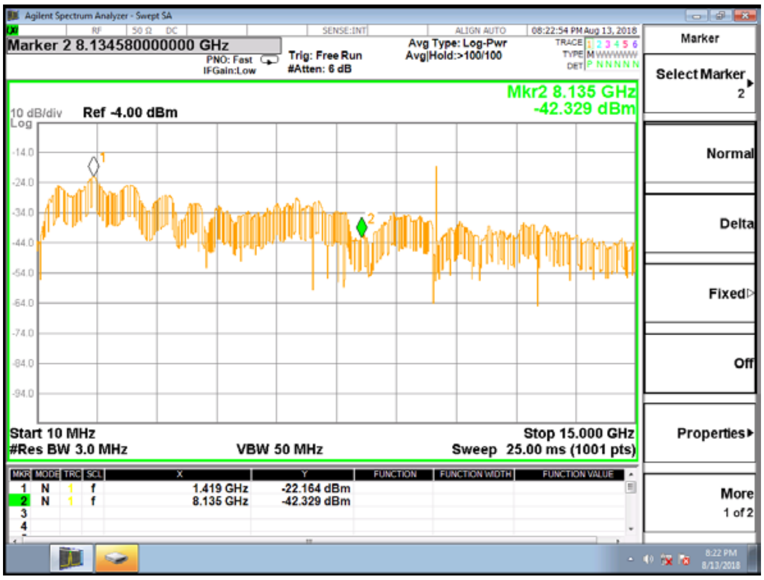

Figure 3. Experimental results.

As shown in the figure above, the higher the frequency, the greater the loss of frequency conversion, of which 61.4 GHz frequency conversion loss is the smallest, so it is recommended to use about 61 GHz frequency band for testing, which is more efficient.

As shown in the table above, when the horn antenna is obliquely aligned, the received signal of the spectrum analyzer is caused by the reflection of the test environment, i.e., the transmission loss is caused by the propagation and reflection loss of the environment; when the PCB board is placed in front of the horn antenna, the transmission loss is reduced, and it is suspected that the reflection of the PCB board to the high frequency signal increases between the up and down converters. Shielding network is added to block the reflection signal of the gap; when the shielding network is added, when PCB board or aluminium tube is placed in front of the horn antenna, the transmission loss increases, indicating that the power line surface wave has not formed, but reflects the signal of the gap, which is the increase of the transmission loss of the signal in the environment.

4.3. Analysis of Test Results

The surface wave phenomenon was not detected in the test results. The experimental principle is analyzed: (1) The energy is directly reflected by the rectangular waveguide irradiating the metal or dielectric-coated conductor at different incident angles, but not gathered on the surface of the conductor. (2) The radiation efficiency of rectangular waveguide is low, and most of the energy can not be transmitted effectively. (3) Metal rods have no dielectric layer, or the dielectric layer is too thin to bind most of the energy to the surface of conductors.

According to the theoretical and simulation analysis, the directions to be improved are: 1) using Power Line with dielectric layer thickness to test; 2) improving the energy coupling device.

5. Summary

In this paper, through theoretical analysis, calculation and numerical simulation, a simple radiation and coupling device is designed to verify the transmission of surface wave.

However, the results of this stage are based on simple experimental devices, and the transmission of real power lines needs to be further improved in terms of test configuration, excitation and coupling devices, and the performance of UWB signal transceiver needs to be further tested. The coupling device between transmitter and receiver is very important, which involves antenna technology, wave aggregation technology, dielectric construction technology and so on. Next, the direction of realization can be defined as using dielectric lens to collect and extract electromagnetic waves.

6. References

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