Antennas in a waveguide propagation environment

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Abstract

In this paper, we discuss antenna properties in a waveguide propagation environment. An example of this environment is heating, ventilation, and air conditioning (HVAC) ducts, which behave as multimode waveguides when used for indoor radio communications. An important antenna characteristic in waveguides is mode sensitivity gain, which is analogous to the antenna directive gain in free-space and is a function of antenna parameters. We demonstrate this with the example of a monopole probe antenna coupled into a multimode cylindrical waveguide.

1 Introduction

Theory and design of antennas radiating into free-space is well established. Another propagation environment of interest is waveguides. The main differences between this environment and free-space are: 1) the waves can propagate only along the waveguide; 2) the propagating field can always be decomposed into a finite sum of normal modes.

If the cross-section of the waveguide where the antenna is located is much larger than the wavelength, the problem can be analyzed using geometrical optics. This makes traditional (free-space) antenna theory applicable for analysis of situations like radio propagation in tunnels [1]. In contrast, if the number of propagating waveguide modes is modest (i.e., few tens of modes), it is more appropriate to analyze fields using modal analysis rather than ray tracing. This is the situation we are addressing in this paper.

The application that stimulated our interest in this topic is indoor communications via HVAC ducts, which behave as multimode waveguides when driven at radio frequencies.

2 Antenna characteristics

An antenna in free-space can be characterized by its directive gain, which is a function of angular direction. An infinite number of antenna radiation patterns are possible in free-space. In waveguides, the only direction of field propagation is along the waveguide. An antenna can be characterized by the waveguide mode distribution that it excites. This concept is illustrated in Figure 1.

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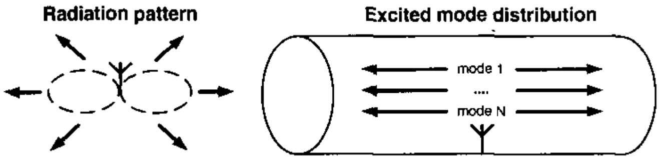

Figure 1: Antenna radiating in free-space (left) and in a waveguide (right).

In waveguides, characteristic analogous to the directive gain is mode sensitivity gain. Assume that waveguide ends are terminated with matched loads (no reflections). Mode sensitivity gain $S(n)$ can be defined via the power $P(n)$ radiated into a mode n, normalized by the total radiated power P divided by the number of modes N:

$$S(n) = \frac{P(n)}{P/N}. \tag{1}$$

Just as directivity is the maximum value of directive gain, sensitivity S can be defined as the maximum value of mode sensitivity gain $S(n)$:

$$S = \max S(n). \tag{2}$$

If all the power is radiated into one mode, then $S = N$.

Table 1 gives a comparison of antenna properties in free-space and in waveguide. As the waveguide cross-section becomes large, the number of modes increases, approaching a continuous spectrum.

Table 1: Comparison of antenna properties in free-space and waveguide environments.

Free-space	Waveguide
Continuous mode distribution	N discrete modes
Any propagation direction	Only along the waveguide
Directive gain $D(\theta,\phi)$	Mode sensitivity gain $S(n)$
Directivity $D < \infty$	Sensitivity $S \leq N$

To date, most researchers have been interested in the impedance of probe antennas coupled into a microwave guide, operated in one- or two-mode regime. The impedance match between the transmitter and the antenna is important since it defines how much power is radiated. However, to build an effective waveguide communication system, it is also critical to be able to excite a desired mode distribution which has favorable characteristics and allows one to reduce the multimode dispersion and minimize the attenuation in complex waveguide systems. For instance, exciting a single mode can eliminate the multimode dispersion in an HVAC duct system.

Many mode selection techniques are known, but most of them involve modifying the waveguide shape or structure [2]. Desired mode selectivity can also be obtained by varying the antenna parameters, which we demonstrate in the following section.

3 Example

One of the simplest antennas is the monopole probe. The characteristics of this antenna, positioned above the ground plane in free-space, are well known. A monopole probe can also be coupled into a waveguide as shown in Figure 2. This type of coupling has been well studied [3]. Typically, a sinusoidal current distribution is assumed on such an antenna. This allows one to calculate mode excitation coefficients and antenna impedance as functions of waveguide diameter, operating frequency, and monopole length. Details of calculations for cylindrical waveguides can be found in [4] and will be used to obtain theoretical results presented below.

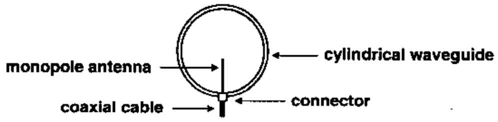

Figure 2: Example: monopole probe antenna in a cylindrical waveguide.

Both in waveguide and in free-space, monopole probe impedance depends on its length. Minima of return loss occur at resonant antenna lengths of $\lambda/4$, $3\lambda/4$, etc. Consider a 30.5 cm diameter cylindrical waveguide, where up to 17 modes can propagate at 2.45 GHz. Figure 3 gives theoretically computed mode distributions excited in this waveguide at 2.45 GHz by the monopole probe with $l = 3.06$ cm ($\lambda/4$) and $l = 9.18$ cm ($3\lambda/4$). One can see that a change in monopole length significantly affects the excited mode distribution. Note that TE_{on} modes are not excited by this vertical monopole. For the short monopole, sensitivity is 7.62 dB (reached at mode TE_{61}). For the long monopole, sensitivity is 5.92 dB (reached at mode TE_{22}).

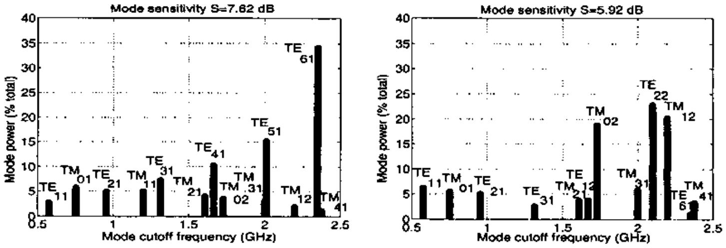

Figure 3: Mode distributions excited in a 30.5 cm cylindrical duct at 2.45 GHz by the monopole probe antenna with $l = 3.06$ cm (left) and $l = 9.18$ cm (right).

The results presented above have been verified experimentally with identical monopole probe antennas coupled into straight circular HVAC ducts 30.5 cm in diameter made of galvanized steel. The frequency response measured between the antenna ports is directly related to mode sensitivity gain, defined by the monopole length. Measured data well agreed with our theoretical predictions. Comparison between theory and experiment and the description of the experimental setup can be found in [4].

4 Discussion

For illustrative purposes, we considered only a simple monopole probe antenna. A vertical radial monopole antenna excites only modes which have non-zero electric field along the antenna. Other types of antennas can be considered as well. For example, a dipole antenna with circumferential arms that lie in the transversal plane would only excite modes with an angular electric field. Even more effective mode excitation characteristics can be obtained with an antenna array which responds well to any mode mix. Antenna elements can be of any type (monopole, dipole, loop, etc.) and can be located along a waveguide, along its circumference, or in a mixed fashion.

Antenna engineering is aimed to design antennas with particular characteristics. In free-space, this usually means antennas which radiate most of the power in a specific direction. In multimode waveguide environment, this means antennas which excite a desired mode distribution. There already exists a great variety of electromagnetic (EM) modelling software for antenna design as well as a multitude of generic EM solvers employing finite element method (FEM), finite difference time domain (FDTD), method of moments (MoM), and other approaches. One can envision that antenna design in waveguides can become a market niche for a new generation of simulation tools. These tools could employ any of the methods mentioned above and would allow one to calculate mode sensitivity gain of an antenna in a generic waveguide, with rectangular and cylindrical waveguides being of primary interest.

5 Conclusions

In this paper we discussed the properties of antennas operating in a waveguide propagation environment. In free-space, the main characteristic is directive gain. In waveguides, the main characteristic of an antenna is mode sensitivity gain. Exciting the desired mode distribution while preserving a good impedance match allows one to design an antenna that not only efficiently radiates the energy into the waveguide but also properly distributes this energy between the modes. We demonstrated this concept with the example of a monopole probe antenna in a cylindrical waveguide. An application of this research is optimal antenna design for indoor radio communications via HVAC ducts.

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