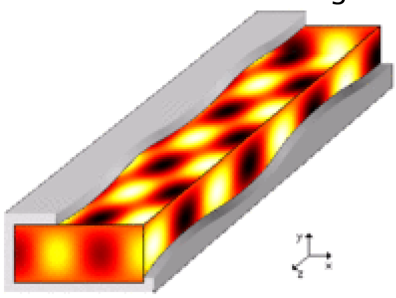
Quantum Mechanics_waveguide

A section of flexible waveguide with apressurizable flange



Electric field inside an x-band hollow metal waveguide.

A **waveguide** is a structure that guides waves, such as electromagnetic waves orsound waves. There are different types of waveguides for each type of wave. The original and most common[1] meaning is a hollow conductive metal pipe used to carry high frequency radio waves, particularly microwaves.

The geometry of a waveguide reflects its function. Slab waveguides confine energy to travel only in one dimension, fiber or channel waveguides for two dimensions. The frequency of the transmitted wave also dictates the shape of a waveguide: an optical fiber guiding high-frequency light will not guidemicrowaves of a much lower frequency. As a rule of thumb, the width of a waveguide needs to be of the same order of magnitude as the wavelength of the guided wave.

Some naturally occurring structures can also act as waveguides. The SOFAR channel layer in the ocean can guide the sound of whale song across enormous distances.[2]

Principle of operation

Example of waveguides and a diplexer in an air traffic control radar

Waves propagate in all directions in open space as spherical waves. The power of the wave falls with the distance *R* from the source as the square of the distance(inverse square law). A wave-guide confines the wave to propagate in one dimension, so that, under ideal conditions, the wave loses no power while propagating. The conductors generally used in wave-guides have small skin depth and hence large surface resistance. Due to total reflection at the walls, waves are confined to the interior of a wave-guide. The propagation inside the wave-guide, hence, can be described approximately as a "zigzag" between the walls. This description is exact for electromagnetic waves in a hollow metal tube with a rectangular or circular cross-section.

History

The first structure for guiding waves was proposed by J. J. Thomson in 1893, and was first experimentally tested by Oliver Lodge in 1894. The first mathematical analysis of electromagnetic waves in a metal cylinder was performed by Lord Rayleigh in 1897.[3] For sound waves, Lord Rayleigh published a full mathematical analysis of propagation modes in his seminal work, "The Theory of Sound".[4]

The study of dielectric waveguides (such as optical fibers, see below) began as early as the 1920s, by several people, most famous of which are Rayleigh, Sommerfeld and Debye.[5] Optical fiber began to receive special attention in the 1960s due to its importance to the communications industry.

Uses

Waveguide supplying power for the Argonne National Laboratory Advanced Photon Source.

The uses of waveguides for transmitting signals were known even before the term was coined. The phenomenon of sound waves guided through a taut wire have been known for a long time, as well as sound through a hollow pipe such as a caveor medical stethoscope. Other uses of waveguides are in transmitting power between the components of a system such as radio, radar or optical devices. Waveguides are the fundamental principle of guided wave testing (GWT), one of the many methods of non-destructive evaluation.

Specific examples:

- Optical fibers transmit light and signals for long distances and with a high signal rate.
- In a microwave oven a waveguide transfers power from the magnetron, where waves are formed, to the cooking chamber.
- In a radar, a waveguide transfers radio frequency energy to and from the antenna, where the impedance needs to be matched for efficient power transmission (see below).
- A waveguide called a stripline can be created on a printed circuit board, and is used to transmit microwave signals on the board. This type of waveguide is very cheap to manufacture and has small dimensions which fit inside printed circuit boards.
- Waveguides are used in scientific instruments to measure optical, acoustic and elastic properties of materials and objects. The waveguide can be put in contact with the specimen (as in a medical ultrasonography), in which case the waveguide ensures that the power of the testing wave is conserved, or the specimen may be put inside the waveguide (as in a dielectric constant

measurement[6]), so that smaller objects can be tested and the accuracy is better.

A sketch of the theoretical analysis

This section's **factual accuracy is disputed**. *(January 2010)*

Electromagnetic wave propagation along the axis of the waveguide is described by the wave equation, which is derived from Maxwell's equations, and where thewavelength depends upon the structure of the waveguide, and the material within it (air, plastic, vacuum, etc.), as well as on the frequency of the wave.

The spatial distribution of the time-varying electric fields and magnetic fieldswithin the waveguide depends on boundary conditions imposed by the shape and materials of the waveguide. Let us assume that the waveguide is made of a metal that is such a good conductor that we can consider it to be a perfect conductor. Nearly all waveguides have copper interiors, but some of them are even plated with silver or gold on the inside - excellent conductors, and also resistant to corrosion. Now, the boundary conditions are these:

- Electromagnetic waves do not pass through conductors, but rather, they are reflected.
- Any electric field that touches a conductor must be perpendicular to it.
- Any magnetic field close to a conductor must be parallel to it.

These boundary conditions eliminate an infinite number of solutions to the wave equation, and the ones that remain are the possible solutions to the wave equation inside the waveguide. The rest of the analysis of the solutions of the electromagnetic waves inside a waveguide gets very mathematical. It can be noted that all solutions are such that either the electric or magnetic field vector must have a component parallel to the axis, in contrast to propagation in a multi-conductor line that can have all its field components in the plane of the cross-section.

All that remains that can be said without getting very mathematical is that commonly used waveguides are only of a few categories. The most common kind of waveguide is one that has a rectangular cross-section, one that is usually not square. It is common for the long side of this cross-section to be twice as long as its short side. These are useful for carrying electromagnetic waves that have a horizontal or vertical polarization to them.

The second most commonly used kind of waveguide has a circular cross-section. These turn out to be quite useful when carrying electromagnetic waves with a rotating, circular polarization to them. Then, its electrical field traces out a helicalpattern as a function of time.

The third kind of a waveguide - actually a seldom-used one - has an elliptical cross-section.

Propagation modes and cutoff frequencies

This section's **factual accuracy is disputed**. *(January 2010)*

A propagation mode in a waveguide is one solution of the wave equations, or, in other words, the form of the wave.[5] Due to the constraints of the boundary conditions, there are only limited frequencies and forms for the wave function which can propagate in the waveguide. The lowest frequency in which a certain mode can propagate is the cutoff frequency of that mode. The mode with the lowest cutoff frequency is the basic mode of the waveguide, and its cutoff frequency is the waveguide cutoff frequency.

Impedance matching

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In circuit theory, the impedance is a generalization of electrical resistivity in the case of alternating current, and is measured in ohms (Ω).[5] A waveguide in circuit theory is described by a transmission line having a length and self impedance. In other words the impedance is the resistance of the circuit component (in this case a waveguide) to the propagation of the wave. This description of the waveguide was originally intended for alternating current, but is also suitable for electromagnetic and sound waves, once the wave and material properties (such as pressure, density, dielectric constant) are properly converted into electrical terms (current and impedance for example).

Impedance matching is important when components of an electric circuit are connected (waveguide to antenna for example): The impedance ratio determines how much of the wave is transmitted forward and how much is reflected. In connecting a waveguide to an antenna a complete transmission is usually required, so that their impedances are matched.

The reflection coefficient can be calculated using: $\Gamma = \frac{Z_2/Z_1 - 1}{Z_2/Z_1 + 1}$, where Γ is the reflection coefficient (0 denotes full transmission, 1 full reflection, and 0.5 is a reflection of half the incoming voltage), Z_1 and Z_2 are the impedance of the first component (from which the wave enters) and the second component, respectively.

An impedance mismatch creates a reflected wave, which added to the incoming waves creates a standing wave. An impedance mismatch can be also quantified with the standing wave ratio (SWR or VSWR for voltage), which is connected to the impedance ratio and reflection coefficient by: $VSWR = \frac{|V|_{max}}{|V|_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$, where $|V|_{min,max}$ are the minimum and maximum values of the voltage absolute value, and the VSWR is the voltage standing wave ratio, which value of 1 denotes full transmission, without reflection and thus no standing wave, while very large values mean high reflection and standing wave pattern.

Electromagnetic waveguides

Main articles: Waveguide (electromagnetism) and transmission line

Waveguides can be constructed to carry waves over a wide portion of theelectromagnetic spectrum, but are especially useful in the microwave and opticalfrequency ranges. Depending on the frequency, they can be constructed from either conductive or dielectric materials. Waveguides are used for transferring both power and communication signals.

Optical waveguides

Main article: Waveguide (optics)

Waveguides used at optical frequencies are typically dielectric waveguides, structures in which a dielectric material with high permittivity, and thus highindex of refraction, is surrounded by a material with lower permittivity. The structure guides optical waves by total internal reflection. An example of an optical waveguide is **optical fiber**.

Other types of optical waveguide are also used, including photonic-crystal fiber, which guides waves by any of several distinct mechanisms. Guides in the form of a hollow tube with a highly reflective inner surface have also been used as light pipes for illumination applications. The inner surfaces may be polished metal, or may be covered with a multilayer film that guides light by Bragg reflection (this is a special case of a photonic-crystal fiber). One can also use small prisms around the pipe which reflect light via total internal reflection [1]—such confinement is necessarily imperfect, however, since total internal reflection can never truly guide light within a *lower*-index core (in the prism case, some light leaks out at the prism corners).

Acoustic waveguides

Main article: Waveguide (acoustics)

An *acoustic waveguide* is a physical structure for guiding sound waves. A duct for sound propagation also behaves like a transmission line. The duct contains some medium, such as air, that supports sound propagation.

Sound synthesis

Main article: Digital waveguide synthesis

Sound synthesis uses digital delay lines as computational elements to simulatewave propagation in tubes of wind instruments and the vibrating strings of string instruments.

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