Novel Waveguide Technologies and Its Future System Applications

Shotaro Ishino

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Abstract

Radio waves are widely used in the fields of communication and sensing, and technologies for sending wireless power are currently being put to practical use. The barriers that have so far limited these technologies are about to disappear completely. In the present study, we examine waveguides, which are a key component of the next-generation wireless technologies. A waveguide is a metal pipe through which radio waves transfer. Although a waveguide is a very heavy component, due to technological innovations, waveguides will undergo drastic modifications in the near future. This chapter introduces trends in innovative waveguide technologies and the latest wireless systems, including communication and power transfer system, that use waveguides.

Keywords: microwaves, radio waves, wave propagation, electromagnetic theory, surface transmission, evanescent wave, components, waveguide, antenna, wireless communication, wireless power transfer, wireless systems

1. Introduction

Electromagnetic waves are waves formed by changing electric and magnetic fields in space. Electromagnetic waves refer to waves with a wavelength of 100 μm or more (3 THz or less). They are described as microwaves or millimeter waves, depending on the wavelength. The existence of electromagnetic waves was predicted by J. C. Maxwell in 1864. J. C. Maxwell proved that the speed at which electromagnetic waves propagate is equal to the speed of light and revealed the fundamental principle that light is propagated in the form of electromagnetic waves [1]. In 1888, H. R. Herth confirmed the presence of electromagnetic waves. This experimentally demonstrated the existence of the electromagnetic waves that was theoretically explained by Maxwell and was shown by the air propagation that Maxwell had not revealed [2]. In 1895, G. Marconi succeeded in wireless telegraphy [3–5]. In Japan, radio broadcasting began in 1925, and television broadcasting began in in 1953. Moreover, to date, electromagnetic waves are used for various purposes ranging from communication and sensing to microwave ovens. Electromagnetic waves are colloquially described as "fluttering in space," and it can be said that life is established by these waves. In recent years, attention has been paid to a technology for wireless power transfer. This technology converts electric power that was previously sent by wire into electromagnetic waves to transmit electricity in space [6–9]. In around the 1900s, N. Tesla tried wireless transmission at a frequency of 150 kHz but failed in his attempts. However, in the 1960s, W. Brown succeeded with his experiments by using microwaves at 2.45 GHz [10]. Research on wireless power transfer is being actively conducted for the range of several-microwatts, used for energy harvesting [11–14] and RFID [15, 16], to the several-kilowatts, used for applications in space in solar power satellites [17–19]. Ultimately, a perfect wireless smart society (**Figure 1**) may be realized in which all wires are unnecessary. As G. Marconi said, "It is dangerous to put limits on wireless." The possibilities of wireless are, indeed, infinite.

However, electromagnetic waves have several drawbacks. As electromagnetic waves propagate, the propagation loss increases because they spread out in space when radiated. This is indicated by the Friis formula [20, 21] and is a physically fixed loss. When the transmission power is Pt, the received power is Pr, the wavelength is λ, and the transmission distance is d, then the transmission equation is as follows.

$$Pr = \left(\frac{\lambda}{4\pi d}\right)^{2} Pt \tag{1}$$

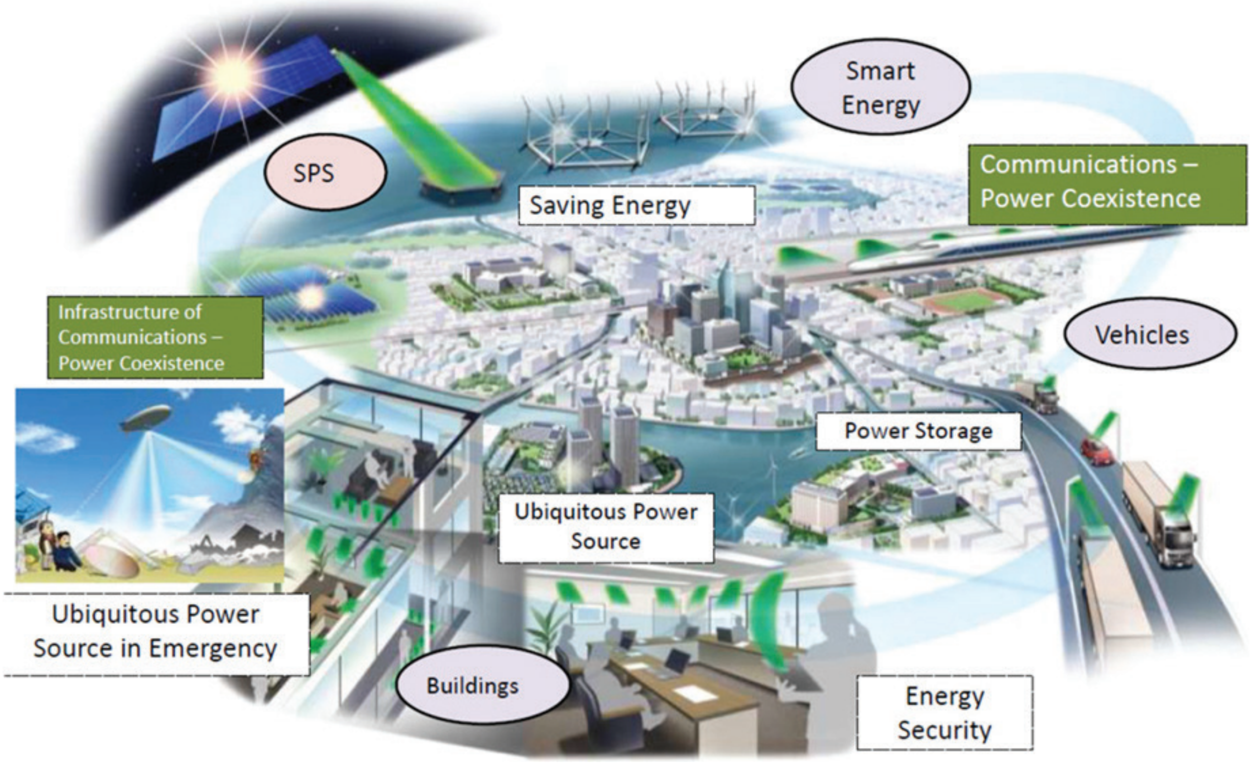

Figure 1. Our dream: wireless smart society [19].

The received power is inversely proportional to the square of the distance and it attenuates. Moreover, if shields are present between transmission and reception of power or if the line of sight is bad, then the attenuation increases further or is completely cut off. Therefore, efficient and reliable transmission is an issue. In the future wireless society, a transmission path that assists transmission lines will play an important role. In this study, we examine waveguides, which are a key component of the next-generation wireless technologies. A waveguide is a metal pipe through which radio waves transfer. Despite being a very heavy component, due to technological innovations, waveguides will undergo drastic modifications in the near future. This chapter introduces trends in innovative waveguide technologies and the latest wireless systems, including communication and power transfer system, that use waveguides.

2. What is a waveguide

A waveguide is a transmission line that transmits electromagnetic waves in a hollow tube (**Figure 2**). Initially, J. J. Thomson and L. Rayleigh et al. came up with the first proposal for such a system [22–30]. Since a waveguide is installed within an enclosed tube, the problem of blocking transmission is solved, thus contributing to improved reliability. There is no fear of power spreading in space; thus, there is no transmission loss. Compared to other forms of transmission, better transmission efficiency is offered by a waveguide. For utilizing the features of waveguides, they are widely used as components for high-power transmission, such as for feeding to an antenna for broadcasting and application between a magnetron and a chamber in a microwave oven. Microwave heating applications are not limited to domestic microwave ovens but extend to industrial applications such as food processing [31–33] and smelting of iron ores [34, 35]. A waveguide is designed to be approximately $\lambda/2$ with respect to the wavelength of the electromagnetic wave to be used if the waveguide is circular in diameter. Moreover, in the case of rectangular waveguide, a waveguide is long side dimension.

The electromagnetic field is a wave that exhibits sinusoidal variation in time. By solving Maxwell's equations and the Helmholtz equations, the solution of the electromagnetic field propagating in the +z direction can be classified into the following three types [36].

$$E_z = 0, \quad H_z = 0;\ \text{Transverse electric and magnetic (TEM)} \tag{2}$$

$$E_z = 0, \quad H_z \neq 0;\ \text{Transverse electric (TE)} \tag{3}$$

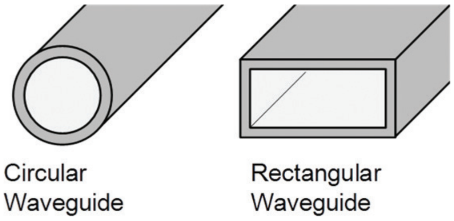

Figure 2. Examples of waveguides.

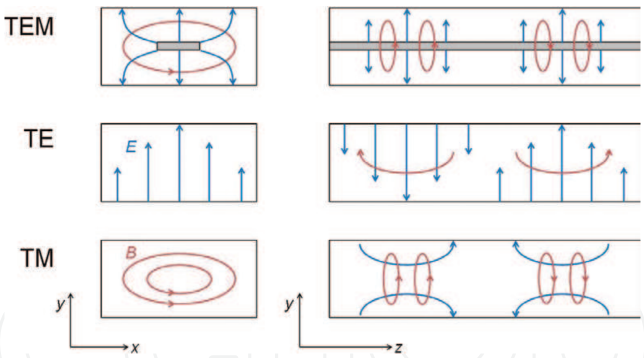

Figure 3. Propagation modes.

$$E_z \neq 0, \quad H_z = 0; \ \text{Transverse magnetic (TM)} \tag{4}$$

An electromagnetic field can be expressed as a combination of three types of waves. The TEM wave has no electromagnetic field component in the propagation direction. The wave is an entirely transverse electromagnetic wave. A plane wave propagating in space, a flat plate line, and an electromagnetic wave transmitted inside the coaxial line are all TEM waves. A plane wave propagating in an electromagnetic field can be expressed as a combination of three types of waves. Space, a flat plate line, and an electromagnetic wave transmitted inside a coaxial line are TEM waves. The states of the electric and magnetic fields in the x–y plane perpendicular to the propagation direction of the TEM wave are the same as those of the electrostatic field and the static magnetic field. Because there is no electrostatic field in the tube surrounded by the conductor wall of the same potential, the TEM wave does not propagate to the waveguide. In order to propagate the TEM wave, it is necessary to use a transmission path comprising two or more insulated conductors.

TE and TM waves are generated in the waveguide. The TE wave is also known as the H wave. The z component of the electric field E is an electromagnetic wave with $Ez = 0$. The electric field is a transverse wave. The magnetic field is a longitudinal wave. In a rectangular waveguide, electromagnetic waves are transmitted with the TE wave as a basic mode. The TM wave is also known as the E wave. The z component of the magnetic field H is an electromagnetic wave with $Hz = 0$. The electric field is the longitudinal and transverse waves, and the magnetic field is the transverse wave. The spherical wave propagating in space is a TM wave (**Figure 3**).

A cut-off frequency exists in the waveguide, and a frequency lower than the cut-off frequency is in the attenuation mode (evanescent mode) and cannot be transmitted. That is, it functions as a high-pass filter. Conversely, in the TEM wave transmission, the frequency is arbitrary and there is no cut-off frequency.

3. Novel waveguide technologies

3.1. 3D printing waveguides

3D printers were invented in the 1980s [37, 38], and their applications are spreading rapidly. Originally known as rapid prototyping machine, a 3D printer is a molding machine that specializes in rapid shaping. In recent years, the price of 3D printers has reduced, and home-use

3D printers based on thermal melting lamination are also available for sale. Moreover, for business use, machines that employ the inkjet method, optical shaping, and powder sintering molding are used in the development department of the manufacturing industry. Because 3D prototypes can be made without a mold, they can be made using simple prototyping.

Various reports have been produced on prototypes of waveguides and peripheral components made by resin molding 3D printers [39–43]. Because electromagnetic waves cannot be confined in plastic tubes, it is necessary to make additional conductive membranes on the surface of the pipe. Thus, although a film having high conductivity can be formed by the plating method, the film thickness is approximately 1 μm and so the microwave penetrates into the inside of the film before finally being transmitted. Thus, adequate shielding properties cannot be obtained. There are also examples that employ a conductive paint to achieve a film thickness of approximately 10 μm; however, the conductivity is poor and the loss due to the conductor becomes large. Moreover, these are mainly microwave components. For millimeter wave components, fine processing is required, which is difficult to realize with the current processing precision.

Moreover, evaluation of several resin materials of the acrylonitrile butadiene styrene such as the resin used in the optical fabrication method revealed that the value of the imaginary part of the dielectric constant, which is a factor of the loss of electromagnetic waves, is relatively large. In the future, it is desirable to develop low-loss materials and molding methods for microwave components.

Moreover, 3D printers capable of directly molding metallic materials are also being used. Metal powder can be sintered by selective laser sintering or selective laser melting. As a result, processing of the conductive film and losses due to resin are eliminated. However, unevenness is formed on the surface, and there can be a problem with the surface becoming very rough. As surface roughness decreases, the conductivity of the surface decreases conduction loss increases. Currently, aluminum alloys are mainly used in 3D printing as materials, but a practical use of copper-based materials is progressing. If the conductivity of the material improves, this loss can be expected to decrease. We fabricated a 10-GHz rectangular waveguide and evaluated its characteristics (**Figure 4**). As a result, there was a transmission loss of approximately 1.5 times than that of the usual waveguide. There was also a leak from the flange portion. The connection was improved by polishing unevenness, but additional work is still required.

3.2. Hose-type waveguide

Weight reduction of the waveguide is done by using resin, but the structure of the waveguide has remained as a non-hollow, solid pipe. Therefore, we are developing a flexible waveguide that is like a water hose. Besides improving convenience by making the pipe flexible like a

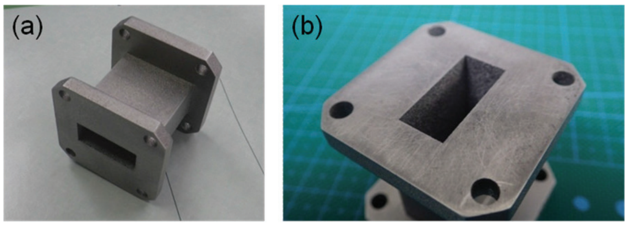

Figure 4. (a) Metallic rectangular waveguide and (b) polished surface.

hose, the image changes and the application range may expand. We introduce an example in which a waveguide is made by winding a copper foil in a hollow resin hose [44].

Our waveguide is a hollow, soft-resin hose with a conductive coating on the outside for electromagnetic wave transfer. Conventional metal waveguides undergo passage, return, and conductive losses, which should be reduced as far as possible. Resin waveguides generate additional dielectric and radiation losses. The dielectric losses are due to absorption by the resin, and radiation losses occurs by leakage due to the insufficient shielding of the thin-film conductor. Dielectric and radiation losses are the dominant loss components in resin waveguides (**Figure 5**).

In this study, we use a soft elastomer material with excellent properties for forming flexible waveguides. In the 10-GHz band, the relative permittivity and dielectric loss tangent of the resin are $\varepsilon'r = 2.28$ and $\tan\delta = 0.00072$, respectively, ensuring very low losses as in a Teflon.

Conversely, the conventional metal-film-deposition techniques of plating, sputtering, and vapor deposition are limited to conductive films with submicron thickness. The required thickness at 10 GHz, estimated from the skin-depth relationship, is at least 10 μm. Therefore, the film in our prototype was formed by winding an 18-μm-thick copper foil around the aforementioned resin hose. We investigated several types of foil winding and found that the lowest radiation loss occurs in the H-center configuration of the waveguide.

The prototype (**Figure 6**) weighs 67 g/m and costs $1.3 per meter, enabling a lightweight and inexpensive waveguide. The waveguide has a low loss and low emission, with a transmission characteristic of −0.39 dB/m in the 10-GHz band.

In future application to automated vehicles, it is necessary to install various sensors, e.g., high-quality inter-vehicle cameras [45–50] that requires transmission speeds on the order of several Gbps [51] with high security. Conventional wire harnesses cannot tolerate external noise in transfers on the order of several Gbps. Because the influence of noise increases with transmission speed, we believe that it is necessary to review the transmission line design. As shown in **Figure 7**, the proposed waveguide is laid from the front to the back to transmit a camera image. The camera image was transmitted inside the waveguide by using high-speed communication between sensors.

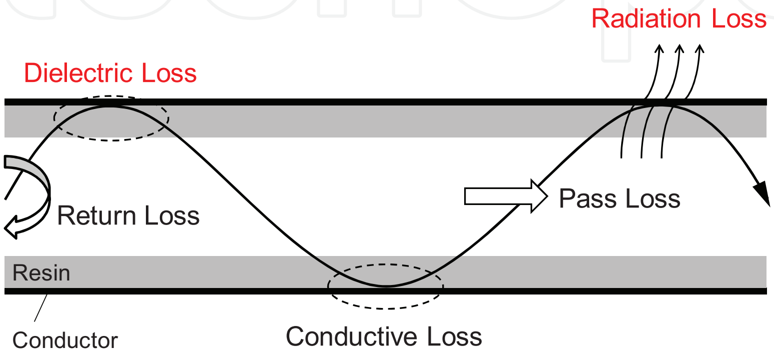

Figure 5. Loss factors in the resin waveguide.

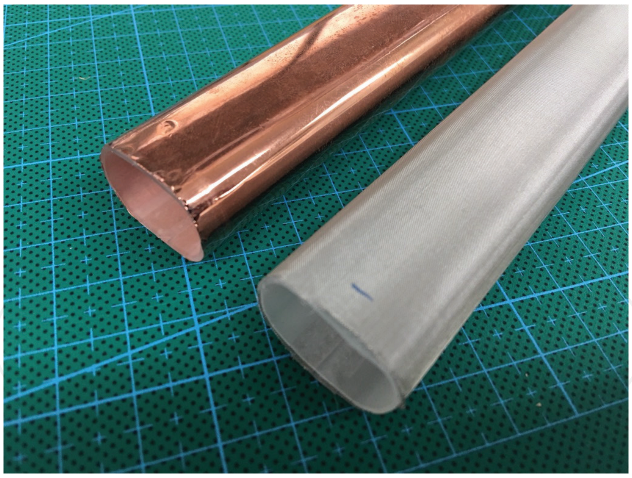

Figure 6. Hose-type waveguides.

3.3. Sheet-type waveguide

Research on two-dimensional communication by using electromagnetic waves that propagate in a thin sheet is progressing [52, 53]. It is assumed that the communication distance is up to several meters. Moreover, by placing a type of antenna known as a coupler at an arbitrary point in the sheet form, close proximity communication inside and outside the seat can be made possible (**Figure 8**). It uses evanescent waves that ooze out of the sheet. The evanescent wave is an electromagnetic wave propagating only near the surface of the sheet. In this way, the sheet-shaped waveguide does not require wiring for each sensor terminal and does not radiate electromagnetic waves to space. In addition to contribute to improving communication security, a relatively large power can be transmitted without exposing people or objects that are not close to the seat to a strong electromagnetic field. Applications for wireless power transmission are also under consideration. Moreover, in the case of Japan, standard specifications for wireless power transfer in the seat are also in place [54]. For future applications, a power supply for a car while in motion and wearable sensor devices are being considered [55].

3.4. DC waveguide

The conventional waveguide is a high-pass filter and cannot transmit bands below the cutoff frequency. However, if the structure can be revised for direct current (DC) propagation, then

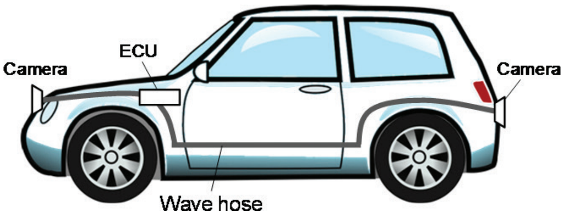

Figure 7. Inter-vehicle communication system.

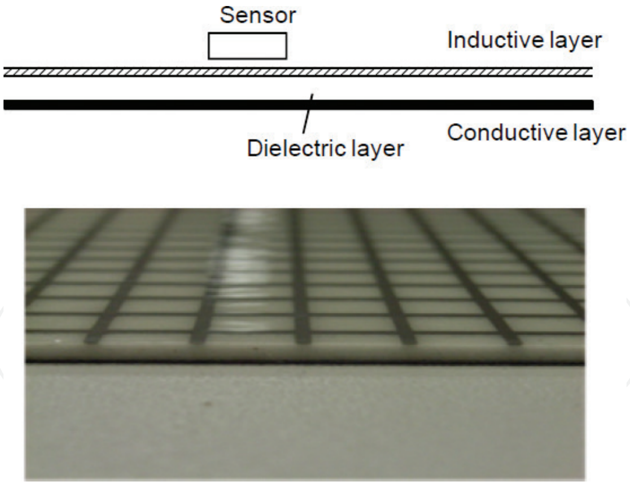

Figure 8. Sheet-type waveguide [52].

high-power transmission becomes possible with a sufficient pipe thickness. We also consider that if a stop band sufficiently far from the pass band can be transmitted, then we can achieve low-frequency communication and sharing in addition to broadband communication. We propose a waveguide with a divided structure that operates not only in a conventional (**Figure 9a**) but also in DC (**Figure 9b**) and parallel line (**Figure 9c**) modes. Subsequently, we investigated whether the waveguide realizes DC in DC mode and can transmit the stop band in a parallel line mode. The conventional mode is a TE10 mode, and the parallel line mode is a TEM mode. It is known as DC waveguide [56].

Although the result (**Figure 10**) differs from simulation results, transmission in the stop band was, at least to some extent, experimentally confirmed. In DC mode, the resistance was approximately 0 Ω, confirming that high-efficiency DC transmission is also possible.

In future work, we will assess the performance of the waveguide in industrial applications. Such plural transmission modes are desired for high-power transmission and broadband communications in automatic driving.

3.5. Substrate integrated waveguide (SIW)

A conventional waveguide is a non-planar three-dimensional circuit, and it is a challenge to fabricate such a waveguide in bulk. SIWs act as an alternative option to conventional waveguides

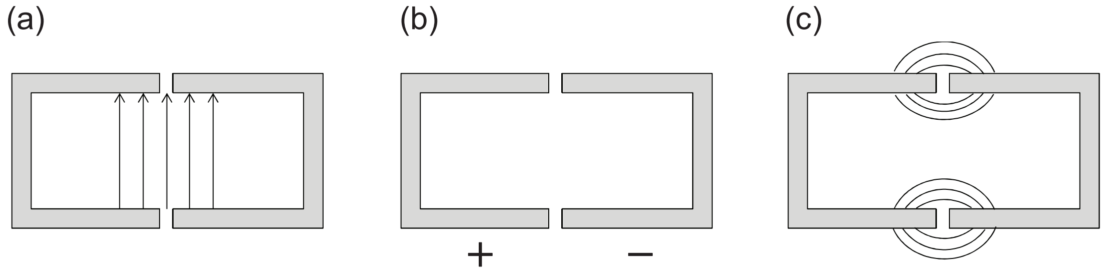

Figure 9. Propagation modes of the split waveguide.

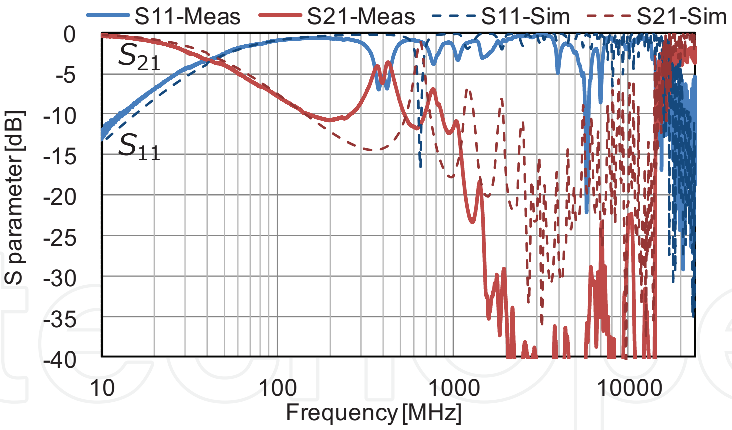

Figure 10. Measured results of DC waveguide.

[57–62]. SIWs are planar structures fabricated using metallic via-hole arrays connecting the top and bottom ground planes of a dielectric substrate (**Figure 11**). A non-planar conventional waveguide can be modeled into a substrate integrated circuit. They are compact, lightweight, cost-effective, and easy to fabricate. Microfabrication of SIW of several microns is also possible, and usage in the terahertz-band order is also expected to be promising.

An example in which a resonance structure is provided in a tube like a conventional waveguide to form a band-pass filter has also been reported [63–66]. We also report an example of fabricating band-stop filters with stacked waveguide structures by SIW [67].

When the microwave is input to the SIW filter, reflection occurs due to a mismatch of the characteristic impedance at the input portion. The microwave input to the filter is distributed at a distribution ratio in the microstrip layer and the waveguide layer. Microwaves entering the microstrip layer ideally do not reflect and propagate. When the microwave entering the waveguide layer is at the frequency of the cutoff region of the waveguide, it propagates while attenuating. Thus, the attenuated portion becomes a reflected wave. Subsequently, at the output of the multilayer substrate filter, microwaves output from the microstrip layer and the waveguide layer are synthesized. Therefore, due to the phase difference of the microwaves output from each layer, propagation waves are canceled at a certain frequency, resulting in reflection. This is the principle that enables an SIW to function as a band-stop filter.

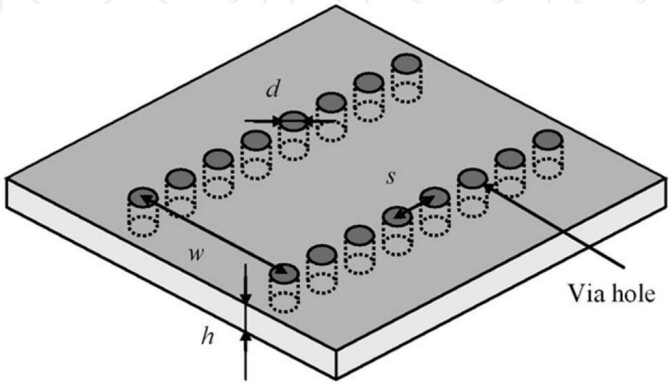

Figure 11. Configuration of an SIW structure synthesized using metallic via-hole arrays [57].

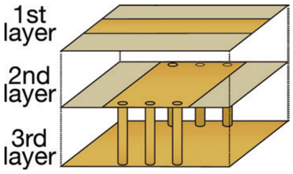

Figure 12. Multilayer SIW filter [67].

In this way, a SIW can easily realize a complicated circuit like a laminated structure. Structures and characteristics that were impossible with a stereo waveguide are obtained and can be expected to be used in various applications. The use of the band-stop filter as the harmonic circuit of the F-class amplifier [68–70] and rectifier [71, 72] are being studied. It can be expected that the efficiency of the microwave circuit can be improved, thus contributing to a low-fuel-consumption society (**Figure 12**).

4. Conclusion

This chapter introduced the novel waveguide technology. The conventional waveguide is characterized as being a large mass of metal, but the proposed waveguide is light, thin, cheap, can change its shape. Thus, waveguides are drastically renewed by the proposed novel technology. Thus, it is time for classic circuits to make a big leap forward.

In addition, along with the technical improvement to the machining technology, a waveguide circuit with a new function can also be realized. We will continue to fuse semiconductor and micro electro mechanical systems (MEMS) processes to develop fine and precise circuit technologies. In addition, we also introduced some application examples. From the microwave band to the terahertz band, the waveguide will be widely used more than ever. In order to realize a sustainable wireless society, the proposed waveguide will prove to be a key component.

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Author details

Shotaro Ishino

Address all correspondence to: shotaroh.ishino.qx@furuno.co.jp

Furuno Electric, Nishinomiya, Hyōgo Prefecture, Japan

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