

Recent Advances in Millimeter-Wave NRD-Guide Circuits

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SUMMARY Though millimeter wave applications have attracted much attention in recent years, they have not yet been put to practical use. The major reason for the failure may be a large transmission loss peculiar to the short wavelength. In order to overcome the inconvenience, it may be promising to introduce the technology of millimeter-wave NRD-guide circuits. In this technology, not only NRD-guide but also Gunn diodes and Schottky diodes play the important role in high bit-rate millimeter-wave applications. A variety of practical millimeter wave wireless systems have been proposed and fabricated. Performances and applications of them are discussed in detail as well.

key words: millimeter waves, NRD-guide, mmNRD-circuits, ASK modulator, BPSK modulator, BPSK demodulator, Costas loop, linear polarized MIMO, uncompressed HDTV

1. Introduction

According to the ITU regulation, electromagnetic waves are divided into optical waves and radio waves at 3 THz. The classification, however, is artificial and millimeter waves seem to possess properties similar to optical waves. By being stimulated by such an idea, a various type of dielectric waveguides have been proposed and studied as a counterpart of optical fiber [1], but practical use of them are limited by radiation loss at curved sections and discontinuities. Though the generation of radiation seems to be unavoidable at first glance, the advent of NRD-guide [2] has solved it. NRD-guide is also expected to be useful for reducing a large amount of transmission loss at extremely high frequencies, hence for putting millimeter wave systems to practical use.

This leads to the idea of millimeter-wave NRD-guide circuits or mmNRD-circuits in abbreviation, in which NRD-guide, Gunn diodes and Schottky diodes play the parts for optical fiber, laser diodes and photo diodes in optical circuits, respectively. By relying on this technology, millimeter wave Giga-bps wireless systems have been developed, and various applications of them have been also proposed.

This paper covers such topics in detail and concludes with a few words for the development of mmNRD-circuits.

2. Principle of NRD-Guide

As described above, the disadvantage of dielectric waveguides is a lot of radiation loss generated at curved sections and discontinuities. The elimination of radiation has been

challenging for the dielectric waveguide development. One of the solutions is to locate a dielectric waveguide in the space where millimeter waves cannot exist.

Such a space can be found at hand. In fact, it is the inside of a below-cutoff rectangular waveguide or a below-cutoff parallel-plate waveguide as shown in Fig. 1. If a rectangular dielectric strip is sandwiched between the below-cutoff parallel plate waveguide, the dielectric waveguide which has the radiation suppression capability can be realized so long as the main electric field of millimeter waves is applied in parallel to the waveguide wall. This is called Nonradiative Dielectric Waveguide or NRD-guide in abbreviation [2]. The structure is depicted vertically in Fig. 1 for the convenience of explanation, but it is usually located horizontally for practical use as shown in Fig. 2.

As an example, the field distribution along an NRD-guide hybrid coupler, which consists of two nearby bends, is illustrated in Fig. 3. It can be seen that millimeter-wave power fed at port #1 on the left moves toward port #2, port #3 in the middle, and finally appears at port #4 on the right. It should be also noticed that any radiation never occurs even if the coupler has a complicated structure. Practical applications of the hybrid coupler will be described in the next section.

3. Components and Devices for mmNRD-Circuits

3.1 Modulator and Mixer

Typical applications of the NRD-guide hybrid coupler are modulators and mixers. Figure 4 illustrates the operation principle of the NRD-guide ASK modulator. Each port, though not expressed explicitly, is assumed to be numbered similarly to Fig. 3. The millimeter wave carrier fed at port #1 moves toward port #2 and port #3 where modulation takes place by a pulse train applied to a pair of Schottky diodes located there, and then leaves via the antenna at port #4 toward the desired direction. It is surprising to see that high bit-rate performance of 1.5 Gbps can be realized by employing a circuit of such a simple structure. This fact clearly demonstrates the inherent advantage of mmNRD-circuits.

If the antenna at port #4 is used for reception in Fig. 4, and the Gunn diode at port #1 for the local oscillator, the IF signal appears at port #2 and #3. This means that the hybrid coupler shown in Fig. 4 can work as a mixer as well.

For reference, simulated and measured transmission characteristics $|S_{41}|$ of the hybrid coupler are shown in

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Fig. 5. Wideband performance can be confirmed.

3.2 Antennas

A specially designed lens antenna has been employed for mmNRD-circuits so far, since it matches with NRD-guide well (see Fig. 7). Though the antenna gain is permitted up to 47 dBi even under the license-free restriction, antenna pointing becomes troublesome if the gain is too large. On the other hand, if the gain is small, the effect of multi-reflection cannot be ignored. Not only antenna gain but also LN amplifier gain must be taken into account together to develop high performance but low cost millimeter wave wireless systems.

3.3 Gunn Diodes and Schottky Diodes

Performances of diodes will be discussed under the license-free restriction. In the technology of mmNRD-circuits, Gunn diodes are exclusively used for oscillators, while Schottky diodes are for functioning devices. Advantages of the Gunn oscillator are a large amount of output power in excess of 10 mW, and phase noise characteristics less than -110 dBc/Hz@300 kHz offset. Under the license-free restriction, transmitted power has to be limited below 10 mW and Gunn oscillators can yield such amount of power without relying on power amplifiers at all. This high performance cannot be expected to any MMIC oscillators.

On the other hand, Schottky diodes are useful for signal processing and can achieve a high bit-rate of 1.5 Gbps or more by means of a simple ASK modulator as shown in Fig. 4. This performance is inevitable for uncompressed HDTV wireless applications.

4. NRD-Guide Wireless Transmitters and Receivers

4.1 Transmitters

Typical NRD-guide transmitters which have been developed so far are shown in Fig. 6. On the left, a fully equipped transceiver, which can transmit and receive at 400 Mbps simultaneously, is shown. It consists of every active and passive components which are needed for satisfactory operation, and has been fabricated in the very early stage of development.

In the middle of figure, another NRD-guide transmitter is shown. The circuit is simple, but performance is quite excellent. It exhibits bit-rate of 1.5 Gbps, which is large enough to support uncompressed HDTV wireless transmission with BER less than 10^{-12} . The transmitter shown on the right side has the coupler of symmetrical structure and exhibits better performance than the others. It should be noticed that transmitters, particularly shown in the middle and on the right-side, are very small in size, but exhibit excellent performance at 1.5 Gbps.

4.2 Receivers

Every transmitter, shown in Fig. 6, can work as a receiver

by employing the Gunn source as the local oscillator, but the frequency stabilization of the Gunn oscillator is by no means easy, since the frequency of the Gunn oscillator is temperature sensitive. Though phase locking by means of a ceramic resonator is effective, it is still time and cost consuming to construct frequency stabilized local oscillators.

In order to overcome such difficulty, direct detection has been tried by using Schottky diodes. After detection, a limiting amplifier can be used to enhance the sensitivity in the similar manner to optical receivers. A fabricated receiver is shown in Fig. 7 in comparison with a wrist watch in size.

Receivers have to be designed carefully depending on the location where they are employed. If the location is limited to indoor, the LN amplifier is not necessarily needed and the cost advantage can be obtained. On the other hand, if outdoor use is dominant, an LN amplifier of an appropriate gain is inevitable hence cost increase cannot be avoided.

By using the transmitter and receiver shown in Figs. 6 and 7, respectively, a millimeter wave wireless system for indoor applications has been constructed. For reference, the eye-pattern observed at bit-rate of 1.5 Gbps is shown in Fig. 8. Excellent performance can be confirmed.

5. Applications of NRD-Guide Wireless Systems

5.1 Wireless Transmission of Uncompressed HDTV

It is quite attractive to apply the millimeter wave transmitter and receiver described above to wireless transmission of uncompressed HDTV data. Though very high bit-rate of 1.5 Gbps is required, the NRD-guide wireless possesses a sufficient performance owing to the low loss and nonradiating nature of the waveguide.

Figure 9 shows a picture of fluttering piece of cloth and its TV image together. Although the cloth is fluttering severely, the real and TV images are identical with each other. This fact clearly shows that the uncompressed wireless transmission is really taking place between the transmitter and receiver.

Another attempt to be noted is the modification of propagation path. In this experiment, the receiver is placed behind the TV set to simulate the situation where millimeter waves are interrupted by crossing persons or obstacles. Usually millimeter waves cannot reach the receiver under such an arrangement, but reflection by a picture frame on the wall can lead millimeter waves to the receiver. By investigating this phenomenon more carefully, a useful mechanism of millimeter wave propagation may be discovered.

5.2 Orthogonal Linear Polarization MIMO Channel

As described above, it is possible to achieve millimeter wave wireless transmission at 1.5 Gbps by means of the NRD-guide wireless system. The next step of development is to further increase bit-rate of transmission. One of the promising techniques is the polarization MIMO channel. There are two types of polarization which may be applied to the

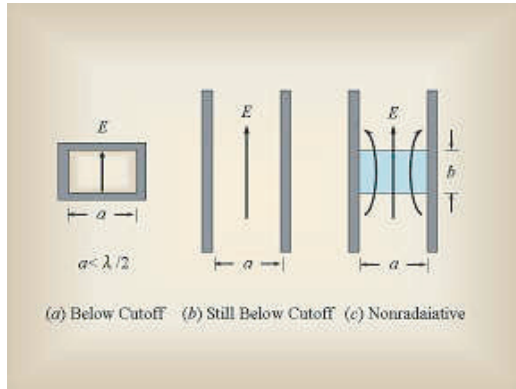


Fig. 1 Principle of NRD-guide.

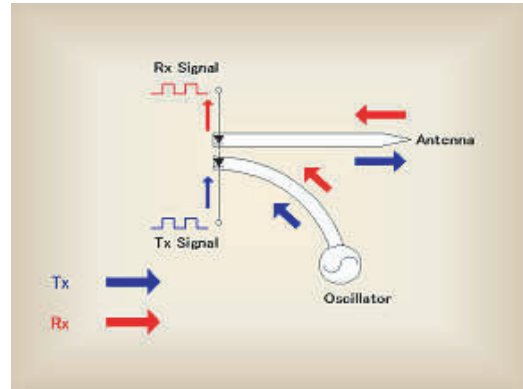


Fig. 4 Principle of modulator and mixer.

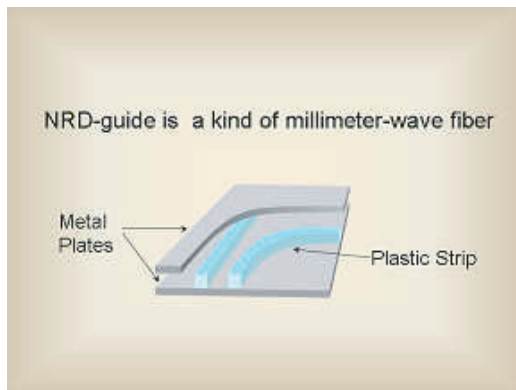


Fig. 2 Practical arrangement of NRD-guide.

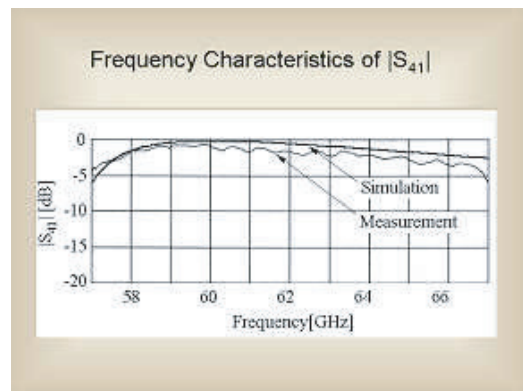


Fig. 5 Transmission $|S_{41}|$ of hybrid coupler.

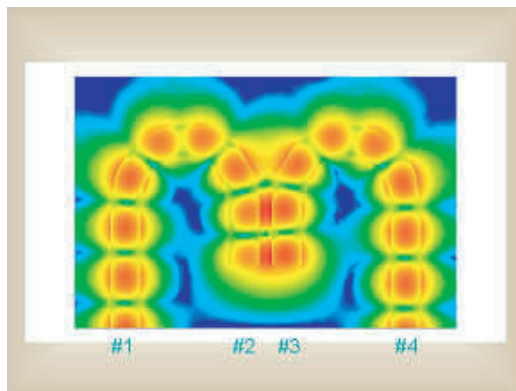


Fig. 3 Wave behavior along NRD-guide hybrid coupler.



Fig. 6 A variety of NRD-guide transmitters.

MIMO channel technique, one being the orthogonal linear polarization, and the other the reverse circular polarization. The preliminary experiment has clearly shown that the orthogonal linear polarization MIMO is better than the reverse circular polarization MIMO because of the less jitter noise characteristics [3].

As an application of the MIMO, wireless transmission of uncompressed 3D images has been tried. Though very high bit-rate of 3.0 Gbps is needed, the experiment is successful and the 3D image can be seen actually through po-

larized glasses.

5.3 Gigabit Downloader

A novel millimeter wave system called “Giga-bit Downloader” has been proposed by our group [4]. The operation of the downloader relies on millimeter wave propagation over a short distance, say, 1m or less, to transmit a huge volume of data as shown in Fig. 10. The system consists of a server memory with a millimeter-wave transmitter to store and send out data such as movies and TV programs, and a



Fig. 7 NRD-guide receiver with lens antenna.

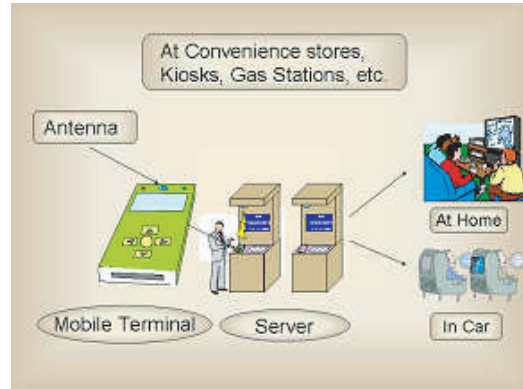


Fig. 10 Scene of Giga-bit downloader.

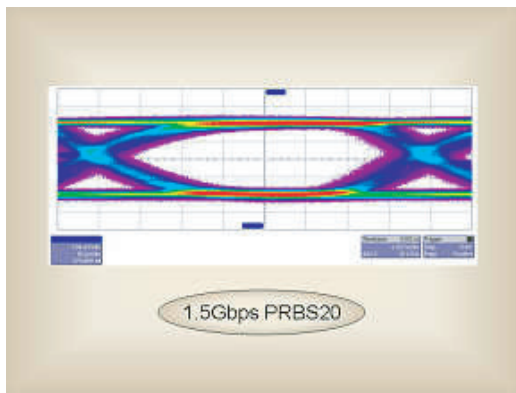


Fig. 8 Eye pattern of ASK signal at 1.5 Gbps.

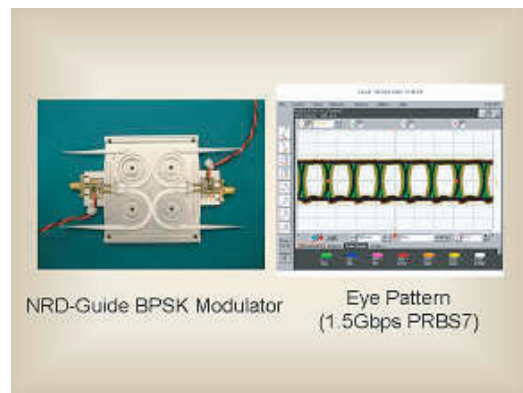


Fig. 11 BPSK modulator and observed eye-pattern at 1.5 Gbps.



Fig. 9 Evidence of uncompressed HDTV (Fluttering piece of cloth and its TV image).

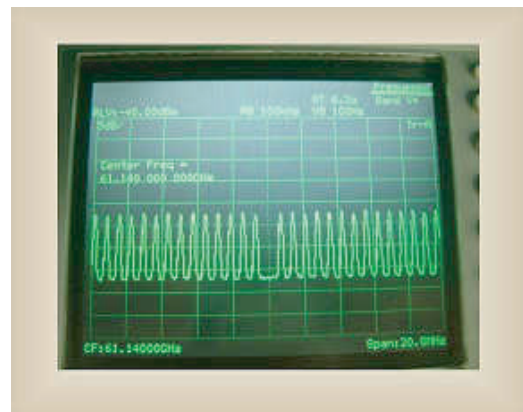


Fig. 12 Spectrum of BPSK modulation.

millimeter wave receiver with mobile memories to capture and store downloaded data. It is supposed that the servers are located at convenience stores, kiosks and other places where many people are likely to gather, while the mobile memories are carried individually. By the experiment, it has been found that performance of the downloader depends on the bit-rate of memory devices such as HDD and SSD rather than the bit-rate of millimeter wave data transmission. The maximum bit-rate which has been observed so far is around 450 Mbps.

5.4 BPSK

Though ASK modulators and detectors have been exclusively employed so far owing to the simple circuit configuration and the reliable performance, BPSK modulators and demodulators have to be also developed in order to extend the possibility of mmNRD-circuits further [5]. In this experiment, the Costas loop is adopted for the phase locking loop.

In the BPSK modulator and Costas loop, the $\pi/2$ phase difference plays an essential role. Such a phase difference can be realized automatically by relying on the inherent property of the hybrid coupler. The circuit configuration of the fabricated BPSK modulator as well as the observed eye-pattern are shown in Fig. 11. By comparing the eye-patterns in Figs. 8 and 11, respectively, better phase noise characteristics of the BPSK signal can be confirmed. For reference, the spectrum of BPSK modulation is also shown in Fig. 12. The figure demonstrates the ideal performance of the modulator for PRBS11 pseudo-random signal with null at the center as well as a series of periodic spectrum peaks outwards.

6. Conclusions

The principle and applications of mmNRD-circuits are described in details. The rules for the development of mmNRD-circuits are summarized as follows:

- (1) Choose low loss material like Teflon for dielectric strips.
- (2) Keep error in thickness of dielectric strips always positive to avoid air gap between the metal plates and dielectric strips.
- (3) Design bends so as to suppress generation of unwanted modes by means of simulation.
- (4) Design good transitions between NRD-guide and printed transmission lines for diode mounts.
- (5) Develop mass production technology of dielectric strips.

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