THEORETICALLY ZERO-LOSS DESIGN OF PLANAR DIELECTRIC WAVEGUIDE Y-BRANCH — AMAZING EFFECT OF SURPENTINE-SHAPED TAPER —

H. Shigesawa, M. Tsuji and O. Tanaka

Doshisha University, Kyoto, Japan

ABSTRACT

A new methodology is proposed for designing planar dielectric-waveguide Y-branch with theoretical zero-loss due to radiation, which designs its taper section so as to control intentionally the intensive power conversion and reconversion between the surface-wave mode and the radiation wave, thereby transforming the input surface-wave mode only into the desired surface-wave mode on the output waveguide, while suppressing the undesired reflection at the input end. The effectiveness of our idea is confirmed by comparing numerical results with those of usual type of Y-branches and also with some measurements that we took.

1. Introduction

Of the planar circuits based on open dielectric waveguides in the millimeter-wave region, branch circuit is one of the basic but most important devices. The guided wave on branch circuit of open structure, however, always losses energy by radiation. This radiation causes serious problems on the circuit performance due to undesired power coupling, or cross talk, with neighboring circuits. Such an effect becomes significant in the millimeter-wave region, because branch circuits are necessary to be designed as compact as possible to the wavelength, even if the junction angle, and the dielectric constant ratio between the core and the surroundings become large and high, respectively.

A typical example of branch circuits is Y-branch which we are discussing here. A general configuration is shown in Fig.1. Many approximate design methods have appeared so far in the literature[1-4]. None of them, however, discussed carefully design problems of Y-branches from the point of view of the actual behavior of both the surface-wave mode and the radiation wave. They have commonly understood that, once the radiation wave is generated, it is scattered to the surroundings and is useless to devise low-loss Y-branches altogether.

According to this understanding, a low-loss Y-branch may be obtained only when the taper shape changes smoothly so that the input surface-wave mode couples to the radiation wave as little as possible. This idea usually needs a quite large dimension to the wavelength for the non-uniform taper section, and such a Y-branch will not be practical in the millimeter-wave region.

This paper develops for the first time a method for designing Y-branches with amazingly reduced loss due to radiation. In a new type of Y-branch, the radiation wave is intentionally generated along the taper, and is controlled so that it can play a quite important role to reduce the loss.

2. Effect of the Intentional Generation of Radiation Wave

In general, the electromagnetic field on a uniform dielectric waveguides of open type can be expressed completely by the constituent fields of both the surface-wave modes and the radiation wave. These constituent fields do not couple each other as long as a waveguide is uniform along the propagation direction. However, if a waveguide becomes non-uniform and/or has discontinuities on it, the power coupling may occur between surface wave modes and also between surface-wave modes and radiation wave.

Let us consider here that only the surface-wave mode is incident from the left-hand side of the plane T_1 as shown in Fig.1. Then the published papers have considered that a low-loss Y-branch is obtained only when the transmitting power of the surface-wave mode is gradually lost along the taper axis and drops monotonically to a certain small value at the output end marked T_2 as shown conceptually by the dashed curve A in Fig.2. This understanding is not correct as shown below.

It is obvious that the surface-wave mode on a practical Y-branch propagates toward the output end, successively repeating, in the greater or less degree,

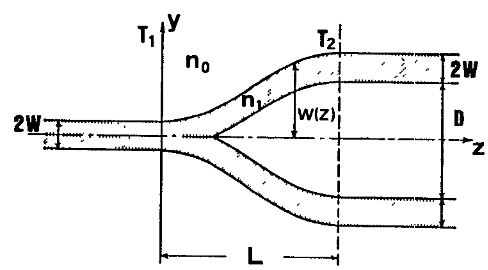

Fig.1. General configuration of dielectric waveguide Y-branch. The structure is uniform in the x direction. An arbitrarily-shaped taper lies between the terminal planes T_1 and T_2.

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the necessary power conversion and reconversion with the radiation wave. Then, it is expected that the power of the surface-wave mode may not change monotonically any more, but complicatedly. Certainly, a numerical example for the practical linear-taper Y-branch discussed in Section 4 exhibits such a power change not like the curve Ⓐ, but like the curve Ⓑ in Fig.2.

The curve Ⓑ shows a sudden power conversion into the radiation wave near the input end, and then it is again reconverted gradually into the surface-wave mode as propagating. But, the power drop of the surface-wave mode at the output end T_2 is inevitable because a taper shape is decided *a prior*. Therefore, such a Y-branch always exhibits the loss due to radiation. However, we can obtain a Y-branch with theoretical zero-loss due to radiation, when the taper shape is designed so as to control intentionally the intensive power conversion and reconversion, thereby transforming the input surface-wave mode into the radiation wave with complete control and finally obtaining only the desired surface-wave mode on the output waveguide, while suppressing the undesired reflection at the input end. In such an ideal case, we may expect conceptually the power change shown by the solid curve Ⓒ in Fig.2.

3. Full-Wave Theoretical Approach

To control intentionally the power conversion and reconversion, it is inevitable to solve the wave behavior on a Y-branch from the view point of the precise boundary-value problem. This is usually quite difficult for the structure of open type. However, we have developed a full-wave theoretical approach based on the mode-matching method. This method approximates a Y-branch by a number of infinitesimal step discontinuities connected each other in tandem as shown in Fig.3(a). According to our equivalent network method[5] which is still amenable to the usual microwave network method, the structure of Fig.3(a) can be expressed by the network of Fig.3(b), which consists of elementary networks of both step and infinitesimal uniform waveguide.

The network parameters expressing completely each of the elementary networks can be controlled by varying each of the guide widths w_i, the separation widths of parallel waveguides d_i and the segment lengths Δl_i (i=1,2,...,N). Then these variables are solved by the modified Newton iteration method to fulfill the given conditions of transforming the resultant field only into the desired surface-wave mode on the output waveguide and of generating no reflection power at the input end, while keeping constant the total length L of a Y-branch and the separation width D of two waveguides at the output end.

4. Design of Low-Loss Y-Branch and Experiments

In this section, we designed a low-loss Y-branch, compared the numerical results with those of usual types of Y-branch, and then with some measurements that we took.

For the first set of calculations, we fixed all of the guide widths w_i to W and the separation width

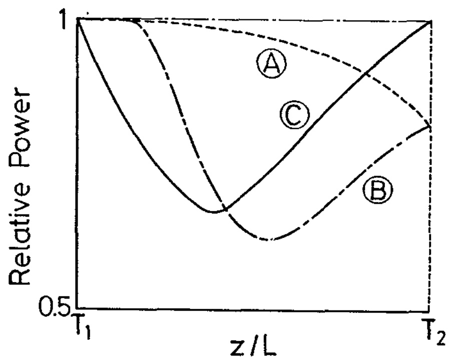

Fig.2. Conceptual curves of the variation of the transmitting power of the surface-wave mode along the taper axis.

D at the output end to $10W$, and we varied each of the segment lengths Δl_i, while keeping L = $15W$. The optimizing procedure was performed for k_0W=1, where k_0=$2\pi/\lambda_0$. For the sake of experimental convenience, the trial design was performed at the X-band, by using the polyethylene (ε_r=2.25) as a dielectric material.

Fig.4(a) shows the Y-branch synthesized at 9.55 GHz (which corresponds to k_0W=1 when W=5 mm). This configuration consists of the serpentine-shaped taper and the abrupt step at both input and output ends. This result indeed seems to be an unexpected one from the usual design point of view, but the prudential physical consideration explains that this result is certainly consistent with our original idea. For example, the solid curve in Fig.4(b) shows the calculated power change of the surface-wave mode for the synthesized Y-branch. While, the dashed curve shows that for the Y-branch which has the same dimension with that of Fig.4(a) except that the serpentine taper is replaced by the linear taper. As is expected, the synthesized Y-branch certainly improves the power drop of the surface-wave mode at the output end. But, there is the residual loss for reason of only the numerical approximations mentioned below.

Fig.5 shows the insertion-loss characteristics as a function of the frequency. The dotted circles indicate the calculations for the Y-branch of Fig.4(a), while the solid curve shows the measured characteristic. It is seen that the agreement is excellently good. In the present design, however, we have approximated the taper section roughly by the segments of N=48 for the sake of saving the calculation time, and the fractional power of 93 percent of the input surface-wave mode is transmitted to the surface-wave mode on the output waveguides. The residual loss will be removed when each of the guide width w_i are considered as variables and the taper is approximated by a larger number of segments in the design procedure.

Fig.5 also presents one more set of the calculation and experiment. The single circles indicate the calculation for the linear-taper Y-branch. We can obviously confirm that the synthesized Y-branch

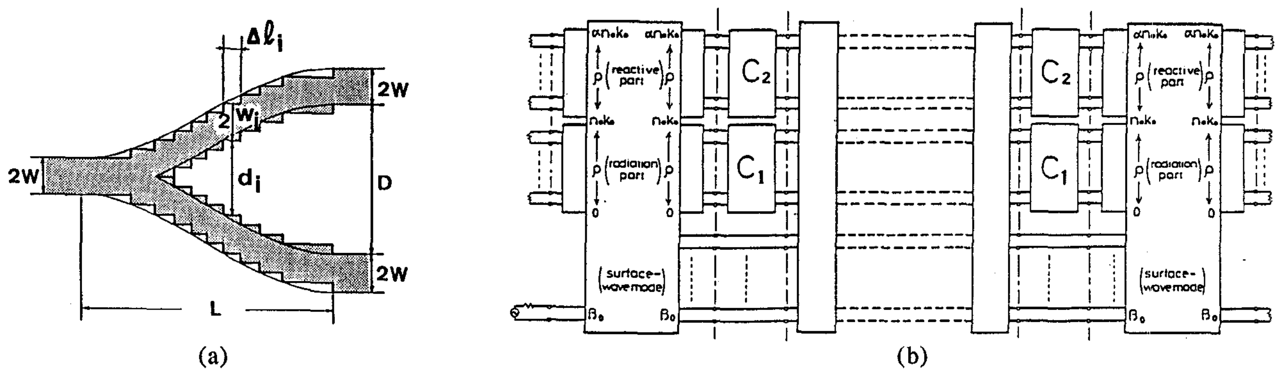

Fig.3. (a) Exaggerated sketch of the step approximation which consists of four types of building block: uniform slab waveguide, step discontinuity on it, coupled-parallel waveguide, and step discontinuity on it. Each of them is completely expressed by its own scattering matrix.
(b) Equivalent network for the structure of Fig.3(a). The large matrices express the step discontinuity and the propagation of radiation wave on a uniform waveguide is expressed by the matrices C_1 and C_2, while the parallel transmission lines are provided for the surface-wave mode.

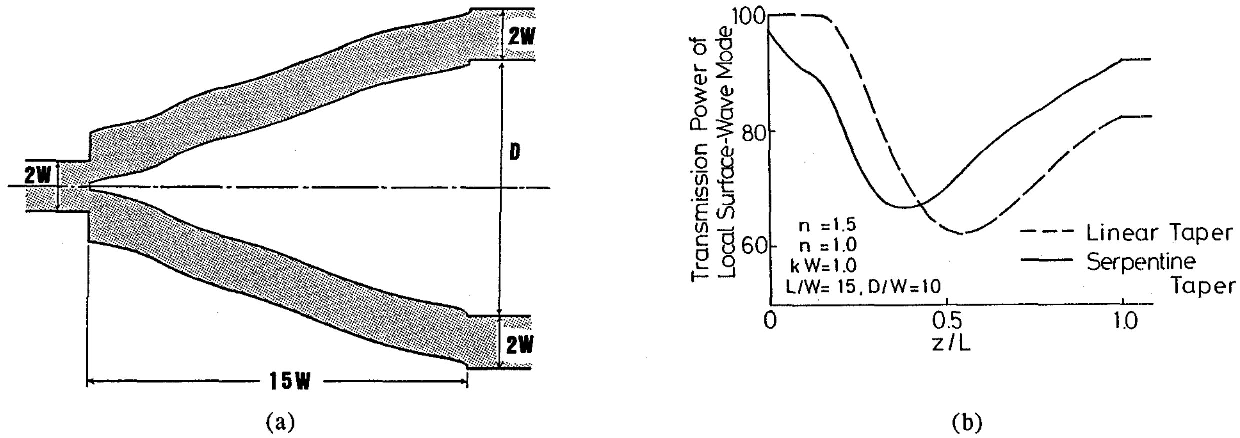

Fig.4. (a) Low-loss Y-branch synthesized at k_0W=1, of which configuration is characterized by the serpentine taper.
(b) Curves of the calculated power change of the surface-wave mode for the serpentine-taper and linear-taper Y-branches.

shows a low-loss characteristic in the wide frequency range, though the optimization is performed at the frequency f = 9.55 GHz.

We have also investigated the Y-branches with the raised cosine and the integrated raised cosine tapers. These are the typical Y-branches in the optical region, and Fig.6 shows the calculated and measured characteristics of the insertion loss as a function of the normalized taper length L/W. It is found that the usual Y-branches mentioned above are accompanied with the radiation loss much larger than that of the linear taper when they are designed compactly to the wavelength, for example, in the region of L/W < 20. For comparison, the measured loss of the synthesized low-loss Y-branch at L/W=15 is shown by the square mark.

The low-loss nature of the Y-branch designed here is also confirmed from the wave behavior around the taper section. Fig.7(a) shows the field intensity distribution for the serpentine-taper Y-branch of Fig.4(a), while Fig.7(b) shows that for the linear-taper Y-branch. It is clearly seen that the serpentine-taper Y-branch smoothly transforms the input surface-wave mode into the surface-wave mode on the output waveguide with the help of radiation wave as we expected. Contrary to this, the radiation wave in the linear-taper Y-branch is scattered away form Y-branch, thereby causing a rather high insertion loss.

Although we have discussed here 2-D structures because of limited available space, but we have been also successful in applying the design method developed here to practical 3-D dielectric-waveguide (*e.g.*, dielectric image-guide) Y-branch, with the help of an unprecedented method for the structural approximation[6]. Also it is obvious that the idea mentioned here is effective to devise low-loss branch component on the planar printed-circuit waveguides, for example, microstrip line, slot line, coplanar

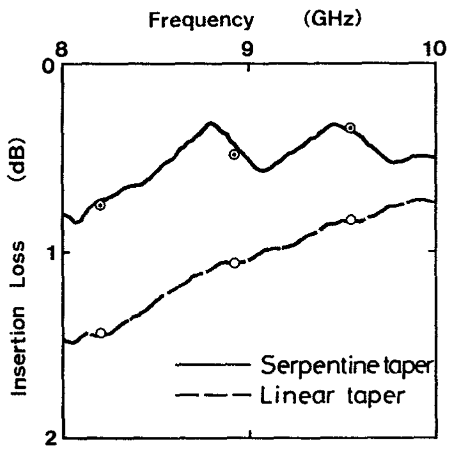

Fig.5. Curves of insertion loss as a function of frequency for the serpentine-taper and linear-taper Y-branches. The optimum design is performed at $f = 9.55$ GHz.

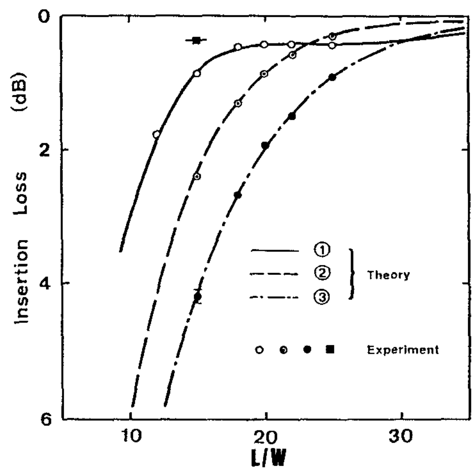

Fig.6. Calculated and measured insertion loss as a function of the normalized taper length L/D for the Y-branches with linear taper ①, raised cosine taper ②, and integrated raised cosine taper③. The square mark on L/W=15 indicates the serpentine-taper Y-branch.

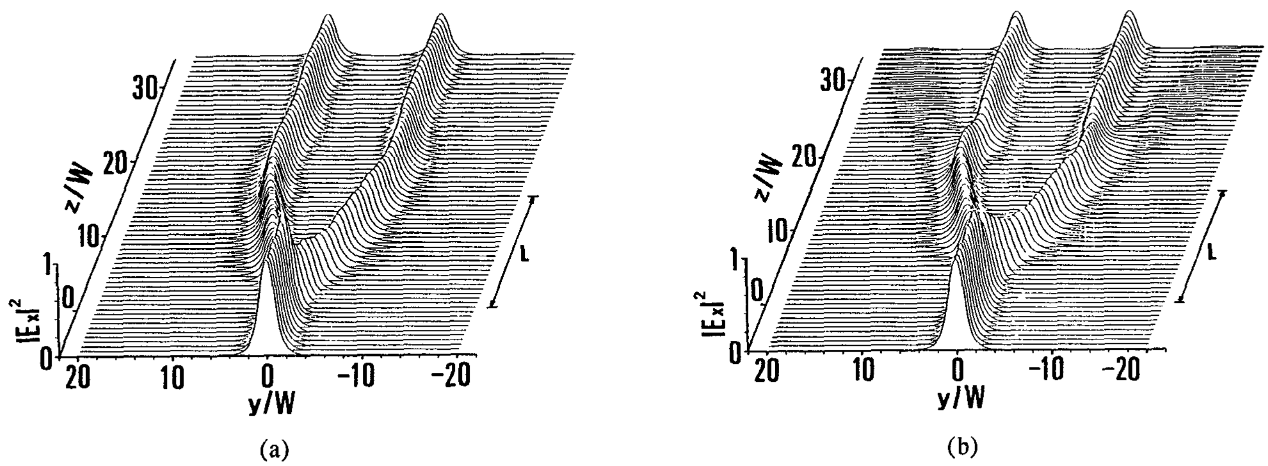

Fig.7. Field intensity distributions around taper section with the length L for the serpentine-taper Y-branch (a) and for the linear-taper Y-branch (b), when only the surface-wave mode is incident from the -z direction.

waveguide, and so on.

Acknowledgments

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