Short Papers

Broad-Band 180° Phase Shift Section in X Band

T. YAHARA, Y. KADOWAKI, H. HOSHIKA, AND K. SHIRAHATA

***Abstract*—The use of an interdigitated coupler and a pair of switching circuits composed of appropriate diodes and two-stub matching circuits is experimentally shown to produce a broad-band reflection-type 180° phase shift section operating at 8.50–10.50 GHz with ± 2° error when fabricated using microwave integrated circuit techniques.**

I. INTRODUCTION

The bandwidth of 4-bit 360° digital p-i-n diode phase shifters fabricated by microwave integrated circuit techniques is usually restricted because of the typical use in reflection-type 180° phase shift section of a narrow-band 3-dB branch-line coupler. Up to this time many types of 180° phase shift sections have been proposed in order to obtain broad-band performance [1], [2], but most of them require many diodes and large circuit dimensions. This is an undesirable tendency since the phase shifters must be small in dimension, light in weight, and driven by as small a power as possible. For these reasons, the 3-dB branch-line coupler is still widely used in spite of its narrow bandwidth. The broad-band backward-wave hybrid coupler has size advantages, but has seldom been implemented in integrated phase shifters.

In this short paper experimental results are described which demonstrate that the reflection-type 180° phase shift section can provide a bandwidth of more than 2.0 GHz in X band, using the interdigitated 3-dB coupler [3], and a pair of switching circuits.

All the circuits are made of microstrip lines on 97-percent aluminum oxide ceramic substrate with a thickness of 635 ± 15 μm and surface finish of 1.5 μm. Both surfaces of the substrate are initially metallized with Au–Cr films, 5 μm and 250 A thick, respectively. The microstrip patterns are made by photolithographic techniques.

II. 3-dB INTERDIGITATED COUPLER

The configuration of the reflection phase shifter is shown in Fig. 1, where ϕ and $\phi + \Delta\phi_{\pm}$ indicate the phase of the input and the output, respectively, and where $Z_{\mathrm{term}\pm}$ means the impedance of the switching circuit. The suffixes + and − mean bias states of diodes in forward and reverse, respectively. $\theta_i (i = 1,4)$ and $Z_i (i = 1,4)$ are the electrical length and characteristic impedance of the stripline elements, respectively. The stripline elements with θ_4 and Z_4 are also used for diode bonding pads. The RF ground of the diodes is taken at the short end of a quarter-wavelength resonator with θ_5 and Z_5, which also serves as an RF choke for the dc bias circuit.

Since the pair of matched diodes is carefully chosen in general, the input VSWR of the phase shifter is largely dependent on the coupler performance.

The interdigitated coupler is well known to have broad-band performance, and it is widely used in L [4] and S band balanced transistor amplifiers [5]. The interdigitated 3-dB coupler in this short paper was designed for X band use with a center frequency of 9.5 GHz as shown in Fig. 2. Crossovers were made with 25-μm gold-bond wires using a nail-head bonder.

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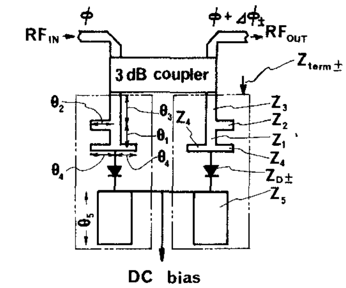

Fig. 1. Configuration of a reflection-type 180° phase shift section.

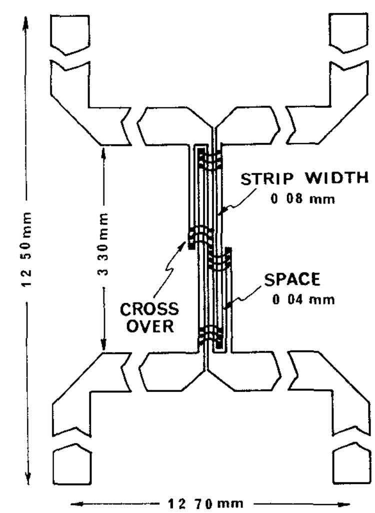

Fig. 2. Top-metallization mask of an X band interdigitated coupler.

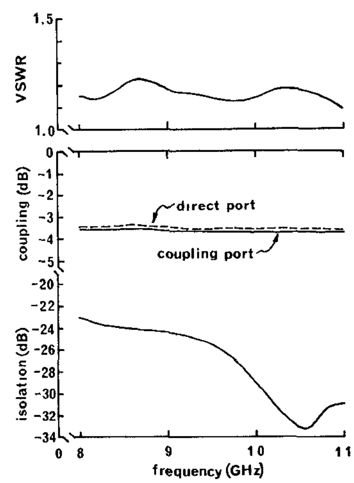

Fig. 3. Performance of an X band interdigitated coupler.

The performance was measured over the frequency band 8.0–11.0 GHz, and the results are plotted in Fig. 3. Throughout the band VSWR is less than 1.25, and the coupling is 3.5–3.7 dB. The isolation is also sufficient for the phase shifter application. The insertion loss is somewhat large, but not so large as to obstruct the phase shifter use.

III. SWITCHING CIRCUIT

As the interdigitated coupler is almost ideal, the performance of the 180° phase shift section is mainly influenced by the switching circuit.

In order to decrease the circuit dimension with elimination of matching circuit elements, it is desirable to choose diodes with impedances of $Z_{D\pm}$ which satisfy $\Delta\phi_d = 180°$ given by (1), at least, at a center frequency

$$\Delta\phi_d = \Delta\phi_- - \Delta\phi_+ = \angle Z_{D-} - \angle Z_{D+}. \quad (1)$$

The matching circuits are, however, provided due to the following two reasons. Firstly, the diode impedances have usually some uncertainties, and hence some matching circuits are required for adjustment to obtain the specified phase shift. Secondly, there are some differences in frequency dependence between $\angle Z_{D-}$ and $\angle Z_{D+}$, which decrease the bandwidth of phase shift. For the compensation of the differences, some matching circuits are required. But in general, the phase and amplitude frequency dependence of the diode switching circuit increases in proportion to the electrical lengths of θ_1, θ_2, and θ_4 in Fig. 1. The increase of their frequency dependence results in decreasing the bandwidth of the phase shift section.

In this short paper, diode parameters are chosen to get 180° phase shift with electrical lengths of the matching circuit elements in two stages for better bandwidth.

The equivalent circuit of the p-i-n diode used here, which is packaged into a Leadless Inverted Device (LID), can be given as shown in Fig. 4. The diode parameters are shown in Table I. This diode is designed to work with a bias of +10 mA at forward bias, and −20 V at reverse bias. When the impedance of the switch is calculated with this diode mounted as shown in Fig. 1, a gap capacitance of striplines between Z_4 and Z_5 is added to C_p by 0.04 pF as a parasitic capacitance.

The values for the matching circuit elements are normalized to 50 Ω for the impedances, and are defined at 9.5 GHz for the electrical lengths. Under the conditions of $Z_i(i = 1,3) = 1$, θ_1 and θ_2 are given 15° and 5°, respectively, by iterative calculations to better bandwidth, but θ_3 is chosen 29° as enough length that the coupler performance is not influenced by the other circuits around it. θ_4 and Z_4 are decided 4° and 1.46, respectively, mainly from the dimensions of bonding pads for LID diodes. θ_5 is 90° due to a quarter-wave resonator, but Z_5 is chosen 0.64 from a dimensional limit.

The calculated and observed $Z_{\text{term}\pm}$ are shown in Fig. 5.

IV. 180° PHASE SHIFT SECTION

The experimented phase shift section is shown in Fig. 6. $\Delta\phi_d$ is adjusted by cutting the end of the stub θ_2. Because θ_4 is used for the bonding pad, it is unsuitable for the adjustable stub. The final length of θ_2 is in good agreement with the calculated. The phase shift calculated from (2) is shown in Fig. 7

$$\Delta\phi_d = \angle Z_{\text{term}-} - \angle Z_{\text{term}+}. \quad (2)$$

The measurements were made with a network analyzer (HP8410A) over the frequency range of 8.0–11.0 GHz, using two bias networks (HP11590A) externally located at the input and output ports of the phase shift section. The results are plotted in Fig. 7. Bandwidth in excess of 2 GHz is obtained in the phase shift performance with ±2° error. The performance is mainly limited by the RF ground of the stub Z_5. The phase shift obtained from the observed $Z_{\text{term}\pm}$, which give a specified 180° phase shift section, is greater than 180° by 10° at the center frequency. It is considered that the difference is caused by the impedance mismatch, etc., of the interdigitated coupler. Nevertheless, broad-band 180° phase shift is obtained with the center frequency of 9.5 GHz and the bandwidth wider than 2 GHz.

V. CONCLUSION

Application of the interdigitated coupler and the switching circuit composed of low-capacitance LID diodes and the two-stub matching circuit has been shown to give a wide-band reflection-type 180° phase shift with center frequency of 9.5 and bandwidth wider than 2 GHz. This phase shift section requires only two p-i-n diodes, small circuit dimensions, and a small drive power.

Many causes can be considered why this structure does not give octave bandwidth as one would expect from the interdigitated coupler. The use of bias stub Z_5 increases the frequency dependence of $\angle Z_{\text{term}\pm}$ and of the difference between them, and decreases the bandwidth of phase shift section. Therefore, the use of a capacitor to ground in instead of the bias stub Z_5 is desirable for better bandwidth. But a fundamental cause restricting the bandwidth of the phase shift section with the interdigitated coupler is considered the difference of phase performances between $\angle Z_{D+}$ and $\angle Z_{D-}$. It is quite difficult to compensate the difference with some matching circuits over an octave bandwidth.

When compared with the branch-line coupler, the interdigitated coupler is found to require more precise dimensional control through

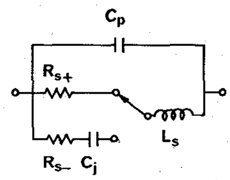

Fig. 4. Equivalent circuit of a p-i-n diode packaged into an LID.

TABLE I
EQUIVALENT CIRCUIT VALUES FOR FIG. 4

parameter	value	measurement conditions
C_p	0.04 pF	at 1 MHz, assured in X-band
L_s	0.8 nH	in X-band
R_s	1.5 ohm	at 10 mA in X-band
R_s	1.5 ohm	at −20V in X-band
C_j	0.18 pF	at −20V and 1 MHz

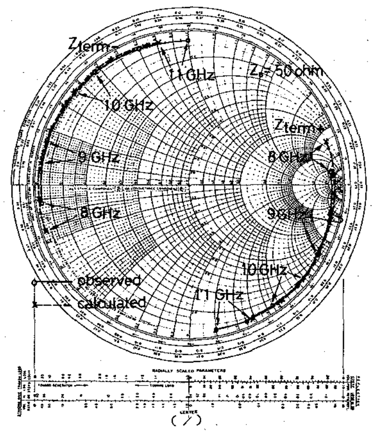

Fig. 5. Calculated and observed impedances of $Z_{\text{term}\pm}$ of the switching circuit.

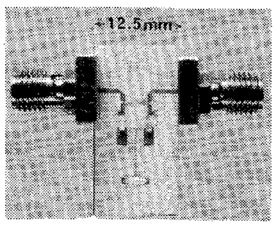

Fig. 6. Photograph of the experimental X band reflection-type 180° phase shift section.

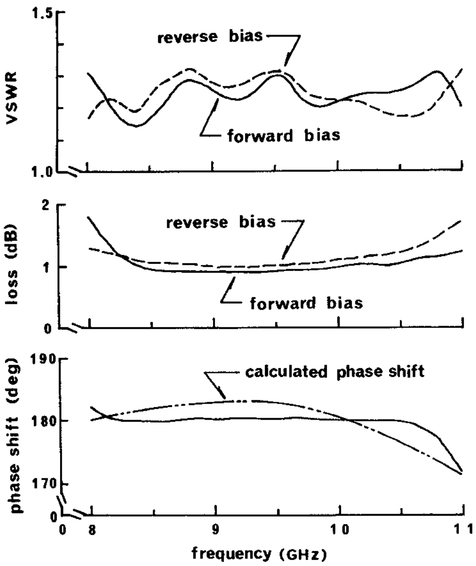

Fig. 7. Observed performance of the X band reflection-type 180° phase shift section.

photolithographic techniques. Its input and output ports are isolated from each other in the dc circuit. But these disadvantages have no serious influence on the phase shifter realization.

The 180° phase shift section described here is very well suited for X band broad-band phase shifters realized in an integrated circuit medium as may be required in a phased array radar.

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Laser Fiber Coupling with a Hyperbolic Lens

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***Abstract*—Substantial improvements in the coupling efficiency from injection lasers to multimode glass fibers have been obtained by spherical lenses melted on the fiber ends. However, the spherical lens has its own drawbacks. It excites high-order modes which are slow and lossy and it becomes less effective when used with graded-index fibers such as Selfoc. This paper proposes a hyperbolic lens which, in principle, is free from these drawbacks. Several samples have been made by first grinding one end of each fiber in a wedge form and then mechanically or flame-polishing the ground surface. These preliminary samples improved the coupling efficiency by a factor of 2–5 over the simple flat-end coupling depending on the difference in the refractive indices of the core and cladding. The improvement is slightly better than that achieved by spherical lenses.**

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I. INTRODUCTION

GaAs double-heterojunction lasers have broad radiation patterns in the plane perpendicular to the junction plane. On the other hand, glass fibers useful for communication applications have narrow acceptance angles. Consequently, when a double-heterojunction laser and glass fiber are put together, only a small fraction of the output power from the laser is usefully coupled into the fiber for transmission. In other words, the coupling efficiency is poor. Several methods have been proposed to improve the coupling efficiency. Cohen [1] first proposed using a cylindrical lens glued to the flat end of a fiber. Later, Cohen and Schneider [2] reported good results obtained with spherical and cylindrical microlenses made from photoresist material. Their work is primarily addressed to single-mode or low-order mode fibers. Independent of this work, Kato [3] proposed a spherical lens fabricated by melting the coupling end of a multimode glass fiber. Although its application is limited to multimode glass fibers, the melted-on spherical lens has a great advantage in that the fabrication is particularly easy.

The theory of the spherical lens has been worked out in detail by C. A. Brackett [4]. In addition to its advantages, the theory indicates that the spherical lens has the following drawbacks.

1) When the core radius becomes small compared to the radius of curvature of the lens, which is essentially equal to the outer radius of the fiber, the improvement of the coupling efficiency becomes small.

2) The spherical lens excites high-order modes which are slow and lossy.

3) The spherical lens becomes less effective when used with graded index fibers such as Selfoc.

This short paper proposes a hyperbolic lens, which is, in principle, free from these drawbacks.

First, the equation of the lens surface will be derived which makes all the rays emitted from a point source and refracted into the glass fiber parallel to the fiber axis. Then the method of calculating the coupling efficiency will be briefly presented, and finally the lens fabrication and efficiency measurements which we have used will be described together with the experimental results.

Admittedly, our fabrication method is still crude but the results already indicate that the hyperbolic lens is worth considering when GaAs injection lasers are to be used in fiber transmission systems.

II. EQUATION OF LENS SURFACE

In this section, the equation of the lens surface is derived which makes all the rays emitted from a point source and refracted into a fiber parallel to the fiber axis. Referring to Fig. 1 the point source is located at 0. The ray emitted from the point source is incident to the lens surface at $\rho(\varphi)$ where φ is the emission angle with respect to the axial direction of the fiber. The incident and refracted angles, θ_1 and θ_2, are related to the refractive index n of the fiber

$$n = \sin \theta_1 / \sin \theta_2. \tag{1}$$

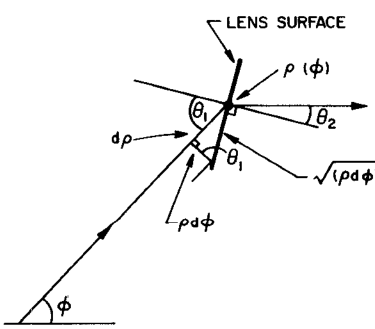

Fig. 1. Derivation of the equation of the lens surface which makes the refracted rays all parallel to the fiber axis.