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V-band directional tandem coupler of monolithic uniplanar structure

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Abstract

We present a uniplanar coplanar-waveguide 3-dB tandem coupler operating at V-band frequencies. The uniplanar structure is monolithically fabricated by using two-section parallel-coupled lines and air-bridge crossovers replacing the conventional multilayer or bonded structures. Due to an optimized tandem structure and non-bonded crossovers minimizing the parasitic components, a maximum coupling of 2.5 dB is measured at 62 GHz with a 2 dB bandwidth of 83%, while a high directivity factor of 33 dB is simultaneously obtained at 58–62 GHz. Over the entire design frequency range of 30–90 GHz, we achieve good phase unbalance of $90 \pm 6.0°$, as well as return loss and isolation lower than −23 and −16 dB, respectively.

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Keywords: CPW; Tandem coupler; Coupled-line coupler; Air-bridge; Directivity

1. Introduction

The directional couplers are fundamental and important passive components extensively used in the realization of a variety of microwave circuits, such as balanced amplifiers, balanced mixers, data modulators, and phase shifters. Due to increasing applications in monolithic microwave IC (MMIC) designs, coplanar waveguide (CPW) devices have also been intensively investigated because of their features such as ease of incorporation of series and shunt elements and suitability for MMICs. When the CPW structure is adopted for the coupler device, a coplanar coupler can have a smaller difference in wave velocities of different propagation modes, which leads to better directivity than with microstrip couplers [1,2].

Various directional couplers have been examined by using the circuit structures based on unit coupling length of a quarter wavelength ($\lambda/4$) and an appropriate analysis of the even–odd mode impedances to achieve the required coupling, directivity and phase difference [3]. The frequency response depends on the coupling circuit structure. For example, edge-coupled line couplers have a wider bandwidth than branch-line and ring-hybrid couplers [4].

The edge-coupled line type is especially well known and widely used for the design of CPW-based directional couplers. However, it is difficult for edge-coupled CPW couplers to achieve a tight coupling effect, such as 3-dB coupling, because critical precision is necessary for the fabrication process. To increase the coupling effect, broadside-coupled and conductor-backed edge-coupled CPW structures were proposed; however, the coupled signal strips should be placed on the opposite side of the substrate in these structures. Therefore, their implementation requires a more complex fabrication process. The degradation of directivity is also unavoidable in the coupled line structure due to the phase velocity mismatch between even and odd modes originating from the difference in permittivity of the materials at the top and the bottom of the transmission line [5].

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When we employ a structure comprising loose-coupled N-section parallel-coupled lines, we can simultaneously achieve tight coupling and high directivity even with a low coupling coefficient of the individual coupler. Tandem couplers take advantage of this by connecting loose-coupled couplers to form a tightly coupled coupler. To fabricate this type of coupler, most research efforts have been made on device configurations utilizing the multilayer or the bonded structure, because a 3-D crossover connection is essential for the tandem structure [6,7].

We adopted an air-bridge structure to materialize the CPW-based tandem coupler as a monolithically fabricated uniplanar structure. Compared to the conventional multilayer or bonded tandem structures, this structure can be made in a smaller size, and more reliable performance is expected at millimeter-wave frequencies (30–300 GHz). In this paper, we report a uniplanar 3-dB tandem coupler with two CPW parallel-coupled lines of a ~8 dB coupling, which can be monolithically integrated with balanced amplifiers and mixers operating at ~60 GHz.

2. Design of coupler

The tightness level of an edge-coupled CPW directional coupler is usually limited by the distance between strips and the strip width. For the conventional edge-coupled CPW structure, the distance between the two signal strips (coupling gap) mainly controls the coupling effect. Fig. 1 shows the characteristic impedances and the effective dielectric constants of odd and even modes, together with the associated coupling coefficients calculated at various coupling gaps (s). As the s decreases, the impedance of the odd mode decreases, so that the coupling coefficient increases, but its value is maintained at less than -4 dB, except for $s < 1$ μm.

Directivity factor, df, is also one of the important characteristics in a directional coupler. It is given by Eq. (1), where P_{isol} and P_{coup} are the powers measured at an isolation port and a coupled port, respectively. The df is degraded with a decrease of coupling or an increase of mismatch between the even- and the odd-mode phase velocities [8].

$$\text{df} = 10\log\left(\frac{P_{\text{coup}}}{P_{\text{isol}}}\right)\ \text{dB}. \tag{1}$$

In the bottom plot of Fig. 1, we show the effective dielectric constants (ε_{eff}) of two different modes calculated at various s for the edge-coupled CPW structure. As the s increases, the mismatch between even and odd modes decreases, so that a higher directivity factor is expected. Therefore, we can minimize, in tandem couplers, the coupling coefficient of individual coupled lines and the degradation of directivity by increasing the number of parallel-coupled lines [9]; therefore, we can extract optimized impedances of even and odd modes for designing a highly directional tandem coupler.

A tandem coupler can be realized by connecting two individual couplers as shown in Fig. 2. In this schematic,

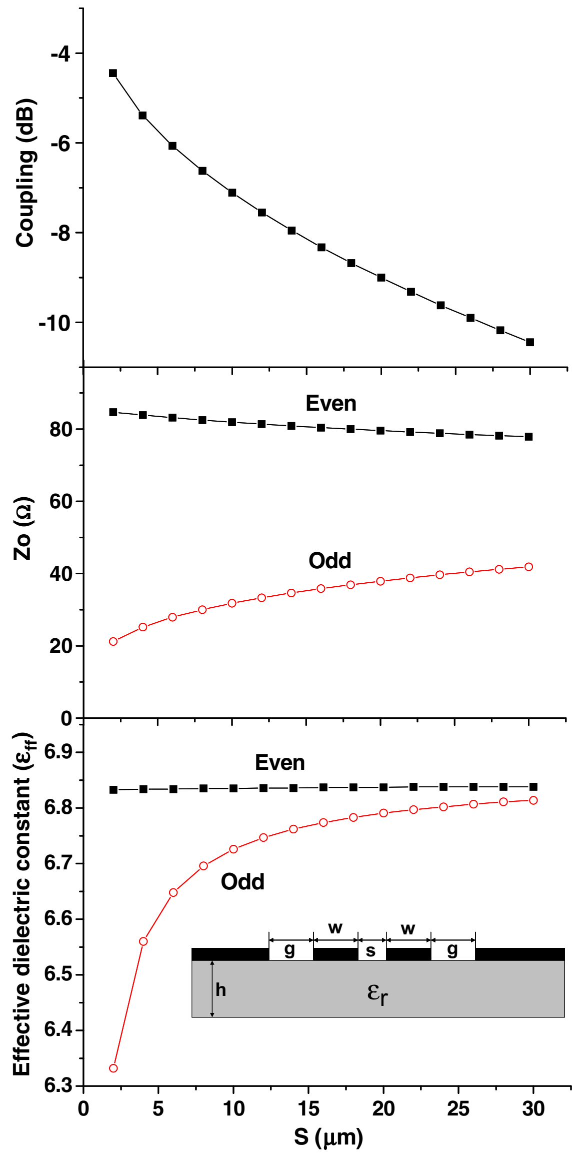

Fig. 1. Effect of the coupling gap, s, on coupling coefficient, characteristic impedance, and effective dielectric constant of the conventional edge-coupled CPW structure (substrate dielectric constant, $\varepsilon_r = 12.9$, $h =$ 680 μm, $w = 26$ μm, $g = 22$ μm and frequency = 60 GHz).

the circled numbers 2 and 3 represent a direct port and a coupled port, respectively, while the number 1 corresponds to an input port. It is obviously easy to realize the high performance coupler structure because of its relatively loose couplings of individual couplers. Furthermore, we can easily design and fabricate a tandem coupler whose coupling coefficient is greater than 3 dB if we can optimize the coupling gap between respective coupler sections. To estimate the coupling ratios for each section, it may be assumed that the signal level is 1 and 0 at the ports 1 and 4, respectively, and that the coupling factor of each section is K. The remaining signal levels of A and B are given by Eq. (2).

$$\text{A} : K \quad \text{B} : -j\left(\sqrt{1-k^2}\right). \tag{2}$$