Analysis and Design of a Diplexer for Satellite Communication System

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Abstract **─** This paper presents the design and analysis of a diplexer for satellite communication system based on hybrid spoof surface plasmon polariton (SSPP) and substrate integrated waveguide (SIW) transmission lines. The proposed diplexer consists of a SSPP printed line composed of H-shaped periodical grooved strips to operate as a low pass filter and a SIW to operate as a high pass filter. The operating frequency bands of the proposed diplexer are from 11.7 to 12.75 GHz for the downlink (DL) band, and from 17.3 to 18.35 GHz for the uplink (UL) band. These frequency bands correspond to the operating frequencies in Nile Sat 201 system. The frequencies of the DL and UL bands are adjusted independently by tuning the structure parameters of SSPP and SIW sections, respectively. The proposed hybrid SSPP-SIW diplexer is fabricated and measured. Simulated and measured results show good channel isolation, low return loss and low insertion loss in the required frequency bands.

Index Terms **─** High-pass filter, Low-pass filter, Spoof Surface Plasmon Polaritons (SSPPs), Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

Highly integrated RF front-end modules with a compact size are important for modern wireless communication applications. The integration of planar microwave structures, such as filters, power dividers and diplexers in the RF front-end, has received comprehensive attentions [1]. Diplexer is one of the fundamental components in a wide variety of wireless communication systems [2], GSM applications and Radar systems [3]. It is a three-port microwave network that can be used to combine both the transmitter and receiver front ends to a single antenna. It isolates the receiver from the transmitter while permitting them to share a common antenna at different frequency bands. An ideal diplexer provides low insertion loss in the two pass bands channel and high isolation between these two bands.

The diplexer design depends on several factors such as frequency response requirements, circuit complexity, size, cost, insertion losses, and isolation. Most design methods used to fabricate diplexers are based on waveguides [4] and planar printed circuits [5]. Despite the interesting electrical characteristics of the waveguides diplexers in terms of high quality factors, selectivity, and low insertion losses, they suffer from many problems in terms of weight, volume and cost. However, planar printed diplexers are much known for their small size, low cost and they can be fully integrated with front end circuits. Hence, the current trend is to miniaturize RF filters and diplexers by designing new planar structures. Combining SIW with SSPP on the same substrate to implement compact-size microwave devices represents one of the recent technologies in planar microwave circuits generally and in planar microwave filters specifically [6, 7].

Substrate integrated waveguide (SIW) is a preferred transmission line as it has the features of both microstrip line and metallic waveguide with the advantages of low profile, low loss and the ability of integration with other planar microwave structures. It consists of two arrays of conducting via holes connecting the top and bottom ground planes of a low loss dielectric substrate to form a configuration which is equivalent to rectangular waveguide [8]. Naturally, SIW is a high-pass filter with a lower cutoff frequency. The dispersion characteristics of SIW can be adjusted by changing the width between the two sets of the via hole arrays, the diameters of the via holes and the spacing between them [10].

On the other hand, SSPP can be developed by using artificial periodic structures which can be used to confine electromagnetic waves within the interface of this periodic structure and the surrounding medium [11]. The SSPP waveguide structures are characterized passband and stopband features [12]. Several investigations are presented for the conversion from quasi TEM wave of microstrip lines to SSPP [13, 14]. On the contrary to SIW, SSPP guiding structures can be configured to develop a low pass filter.

By considering the low-pass characteristics of SSPP and the high-pass characteristics of SIW transmission guiding structures, a hybrid SSPP-SIW microwave diplexer is proposed. The proposed diplexer is designed

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for the NileSat 201 communication system. This system has an uplink (UL) frequency band from 17.3 to 18.35 GHz and a downlink (DL) frequency band from 11.7 to 12.75 GHz [15]. The relative bandwidths of UL and DL bands are 5.89% and 8.59% and the corresponding center frequencies are 17.825 GHz and 12.225 GHz; respectively.

This paper is organized as follows: analysis and design of SSPP and SIW guiding structures are presented in Section II. Section III describes the design of the diplexer based on this hybrid SSPP-SIW structure, followed by an experimental validation. Finally, Section IV presents the concluding remarks.

II. PRINCIPLES OF HYBRID SSPP-SIW DIPLEXER

Figure 1 shows the geometry of the proposed diplexer. It consists of two parallel guiding structures. The upper part represents the SSPP waveguide structure which represents the low-pass filter part. On the other hand, the lower part is the SIW structure which represents the high-pass filter part. These two parts are connected to a single feeding port through a T-junction. Both the SSPP and SIW are tapered to be matched with 50Ω microstrip lines. The following parts of this section present the details for designing each part of this proposed configuration.

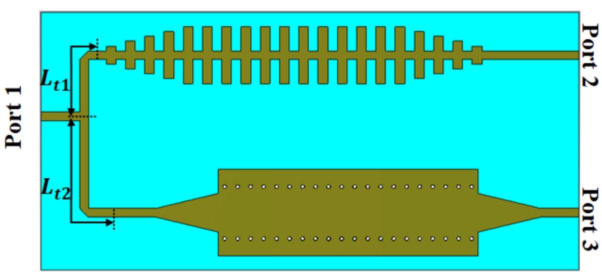


Fig. 1. Configuration of the proposed diplexer.

A. Low-pass filter based on SSPP

The proposed configuration of LPF-SSPP is shown in Fig. 2 (a). This SSPP structure is printed on a grounded dielectric slab Rogers RO4003C with 0.4mm thickness, relative permittivity of 3.55 and loss tangent 0.0027. The metal thickness is 0.035mm. The SSPP structure is composed of a microstrip line loaded by periodic open stubs on its two sides. Two tapering sections are used as transitions from SSPP to the feeding microstrip lines at the two ends of the SSPP structure. These transition regions represent matching sections which smoothly transform the waves in the feeding microstrip lines to SSPP waves. In this transition region, the lengths of successive stubs are varied by a step of 0.5 mm from h_1 to h_4. The second region is the SSPP part, which is composed of periodic open circuit stubs with a unit cell as shown in Fig. 2 (c). The width of the line, periodic step, spacing between stubs, and length of the stub are defined as w, p, a, and h, respectively in Fig. 2 (c).

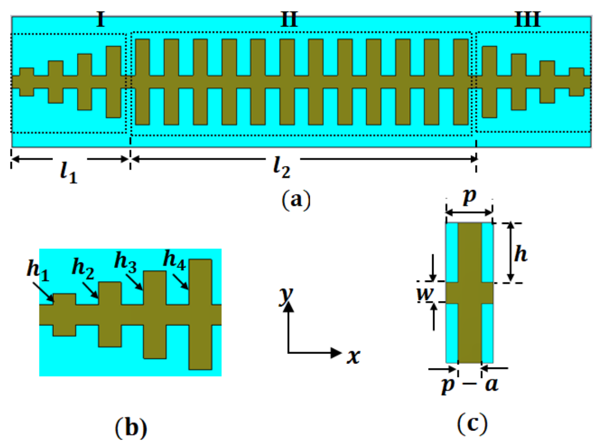


Fig. 2. Schematic of: (a) SSPP section, (b) matching transition part, and (c) SSPP unit cell.

The dispersion relation of this SSPP structure is given by [6]:

$$k_x = k_0\sqrt{1 + \frac{a^2}{p^2}\tan^2(k_o h)}, \qquad (1)$$

where k_x is the propagation constant of the SSPP mode along x-direction and k_0 is the free space propagation constant. The above analytical form is also verified by using numerical simulation based on eigen-mode solver of CST Microwave Studio with periodic boundary conditions in x-direction to calculate the dispersion characteristics of the proposed SSPP structure. Figure 3 shows a comparison between the theoretical and numerically simulated dispersion diagrams of the proposed SSPP structure for different values of h. The other parameters of the SSPP structure are fixed as w =0.9 mm, p = 2 mm and a = 1 mm. It can be noted that the dispersion curves of SSPP are gradually deviated to slow wave region as the value of k_x is increased. Also, the cutoff frequency decreases as the value of h increases from 0.5 mm to 2.5 mm. For the present case, where the cutoff frequency of the LPF is less than 17 GHz, the value of h =2.5 mm would be quite sufficient since the obtained cutoff frequency is nearly 15 GHz.

The complete LPF, based on this SSPP structure, is shown in Fig. 2 (a). It has the following dimensions: w = 0.9 mm p = 2 mm, a = 1 mm, h = 2.5 mm, l_1 = 8 mm and l_2 = 24 mm. The simulated reflection and transmission coefficients of this LPF are shown in Fig. 4. It can be noted that SSPP structure act as a low pass filter with cutoff frequency of 14.4 GHz according to the dispersion relation given in Fig. 3. In the required DL frequency band (11.7 to 12.75 GHz), the insertion loss S21 in the pass band is less than -1 dB while the in the stop band it is greater than -40 dB. In addition, the reflection coefficient S11 in the pass band is less than -10dB.

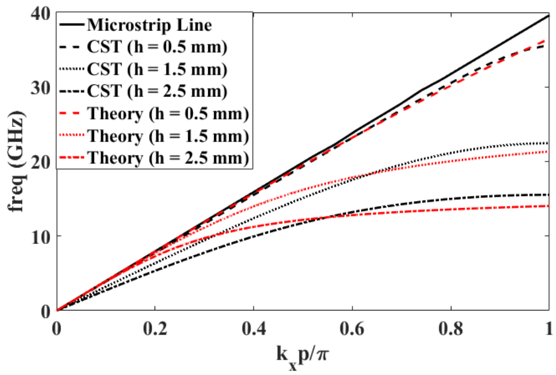


Fig. 3. Simulated dispersion diagram of the Spoof unit cell with different values of groove heights h.

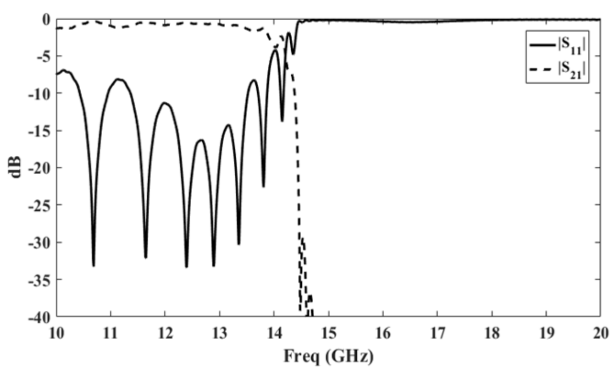


Fig. 4. Simulated S-parameter of LPF section.

B. High-pass filter based on SIW

The proposed geometry of HPF-SIW is shown in Fig. 5 (a). The SIW is designed on the same substrate parameters of the SSPP structure discussed in the previous section. The SIW waveguide is designed to pass the signal of the UL frequency band (17.3 to 18.35 GHz). The characteristic impedance of SIW waveguide is different from the standard 50 Ω feeding microstrip line. Thus, tapered microstrip transitions are used to connect the input/output ports of the SIW as shown in Fig. 5 (b), which are designed as in [9], to achieve a good return loss at the required operating band frequency. The width and length of the tapered microstrip line are w_m and l_m, respectively.

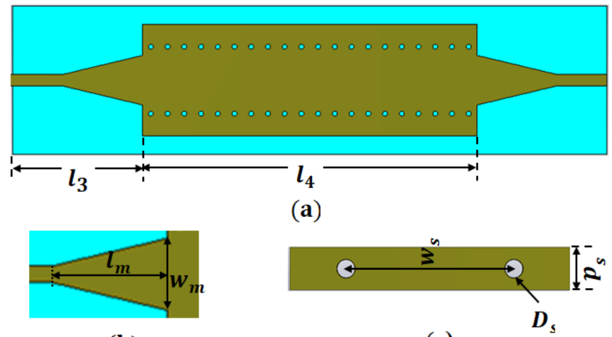


Fig. 5. Schematic of: (a) SIW section, (b) tapered microstrip transition part, and (c) SIW unit cell (clockwise 90° rotation).

The dispersion relation of the fundamental TE_{10} mode in SIW is given by [10]:

$$k_x = \sqrt{\varepsilon_r \mu_r k_0^2 - \left(\frac{\pi}{w_s}\right)^2}, \quad (2)$$

where k_x is the propagation constant of TE_{10} mode along x- direction, w_s the distance between the two rows of the conducting via holes, ε_r and μ_r are the relative permittivity and permeability of the dielectric substrate. The SIW unit cell is shown in Fig. 5 (c). The diameter of the via hole D_s is 0.4 mm and the periodic distance between the adjacent vias p_s is 1.35mm. The dispersion characteristics of the unit cell of SIW for different values of w_s are shown in Fig. 6 based on both analytical and numerical simulations. The SIW supports fast wave with lower cutoff frequency. The cutoff frequency depends on w_s. As the distance between the two via rows increases, the cutoff frequency decreases.

For the present case, it is required to design a HPF to pass the UL frequency band (17.3 to 18.35 GHz). According to the dispersion characteristics of the SIW shown in Fig. 5, it can be noted that the value w_s = 5.4 mm would be quite suitable in this case where the cutoff frequency is around 15 GHz which is below the required pass band and higher than the required stop band.

By optimizing the tapered parameters to achieve matching to 50 Ω impedance, the tapered geometry parameters are w_m= 4mm, l_m = 1.6 mm and the width of 50 Ω line w_{m2} = 0.9 mm. The simulated reflection and transmission coefficients of the designed HPF are shown in Fig. 7. It can be noted that this SIW structure act as high-pass filter with cutoff frequency of 15 GHz as obtained from the dispersion relation given in Fig. 6. In the required UL frequency band (17.3 to 18.35 GHz), the reflection coefficient S11 is lower than -10 dB and the insertion loss is around -0.6 dB.

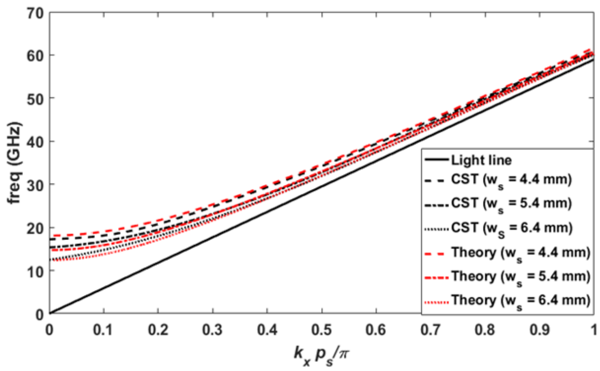


Fig. 6. Simulated dispersion diagram of the SIW with different equivalent widths.

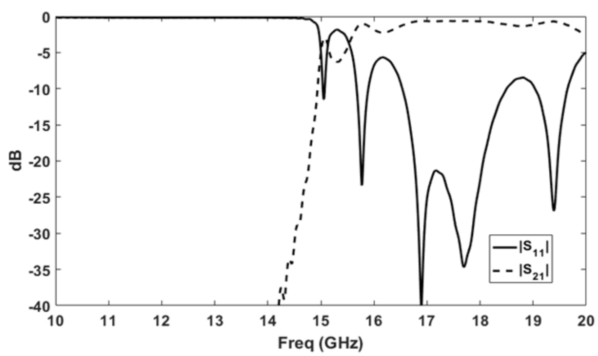


Fig. 7. Simulated S-parameter of HPF section.

C. Design of the feeding T network

From the characteristics of SSPP and SIW, it can be concluded that by combining these two structures it would be possible to design a diplexer with the required frequency bands. The main remaining point in this case is to design an appropriate feeding network which can be used to combine these two structures without degrading their performances; especially in their pass bands. For this purpose, the SSPP-SIW structures are connected by using unequal T-junction power divider. The lengths of the T-junction branches are L_{t1} and L_{t2} which are adjusted to obtain equivalent open circuit input impedance of SSPP and SIW sections at center frequencies 17.825 GHz and 12.225 GHz, respectively. Thus, in the low band the signal flows through the SSPP while the branch of the SIW is isolated by equivalent open circuit and the opposite occurs in the upper frequency band. Thus, the T junction with equal impedance lines is the appropriate configuration for power division in this case. The designed lengths of the T-junction branches in this case are L_{t1} = 7.8 mm and L_{t2} = 12.5 mm

III. RESULTS AND DISCUSSIONS

The designed hybrid SSPP-SIW diplexer is fabricated on Rogers RO4003C substrate as shown in Fig. 8. The substrate has a size is 67 mm × 27 mm, thickness $t =$ 0.4 mm, ε_r =3.55 and $\tan\delta$ =0.0027. The fabricated diplexer is measured by using a vector network analyzer ZVA67. The simulated and measured reflection coefficient S_{11} and transmission coefficients S_{21} and S_{31} are shown in Fig. 9. It can be noted that the transmission coefficient S_{21} indicates low-pass filter in the DL frequency band from 11.7 to 12.75 GHz. In this band, the return loss varies from -25 to -12 dB while the insertion loss varies from -0.9 to -1.7 dB. While the curve of S_{31} shows a high-pass filter in UL frequency band from 17.3 to 18.35 GHz. In this band, the return loss varies from -15 to -10 dB while the insertion loss varies from -1.4 to -2 dB. High isolation between transmitting and receiving ports is realized of over -40 dB as shown in Fig. 9 (d) which is also compatible with the measured isolation in the required operating bands.

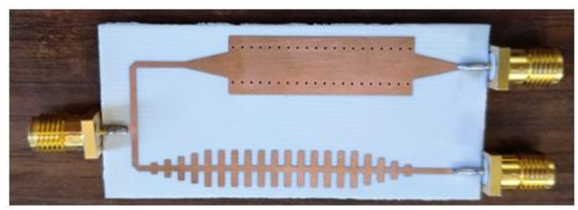
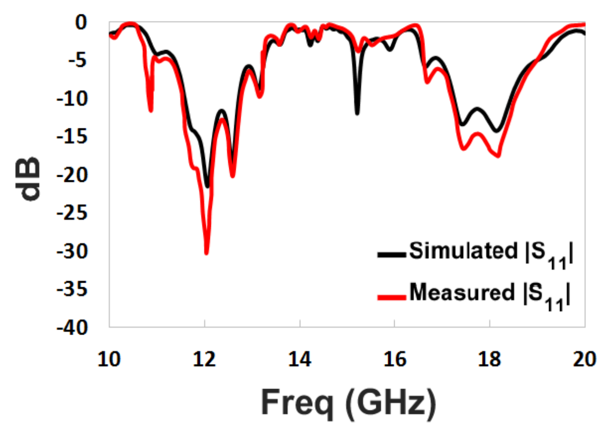
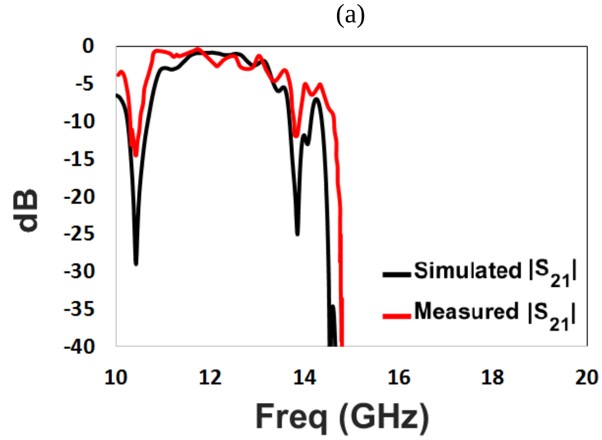


Fig. 8. Fabricated SSPP-SIW diplexer.



(a)



(b)

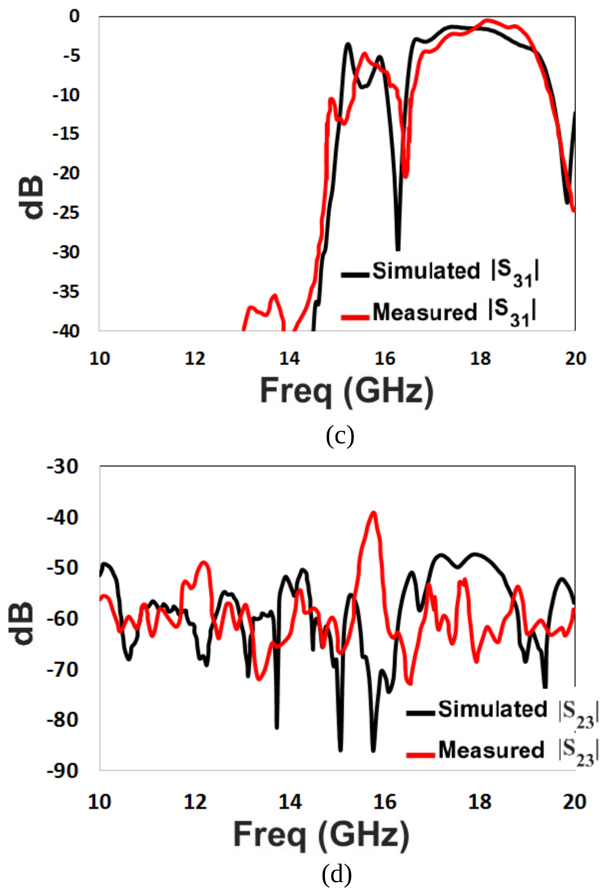


Fig. 9. Simulated and measured S-parameters in dB of the proposed diplexer: (a) return loss $|s_{11}|$, (b) transmission in the lower band $|s_{21}|$, (c) transmission in the upper band $|s_{31}|$, and (d) isolation between port2 and port3 $|s_{23}|$.

The normal component of the electric-field distributions for the proposed the diplexer are shown in Fig. 10 at different frequencies. The observation plane is located inside the dielectric substrate of the diplexer. At the center frequency of the DL band, the SSPP waves are propagating along the upper part as shown in Fig. 10 (a). On the other hand, the signal dose not propagate through the SIW below its cutoff frequency. Within the UL band, the signal can effectively propagate through the SIW as shown in Fig. 10 (c) while it stops along the SSPP part. In the mid-band between the DL and the UL bands, the signal is highly attenuated at both SSPP and SIW as shown in Fig. 10 (b).

IV. CONCLUSION

A new diplexer is proposed based on the low-pass feature of the SSPP structure and high-pass feature of the SIW structure. The signal propagate through the diplexer through SSPP at the DL operating frequency band and through SIW at the UL frequency band. The return loss, transmission and isolation characteristics of the proposed diplexer are simulated and measured.

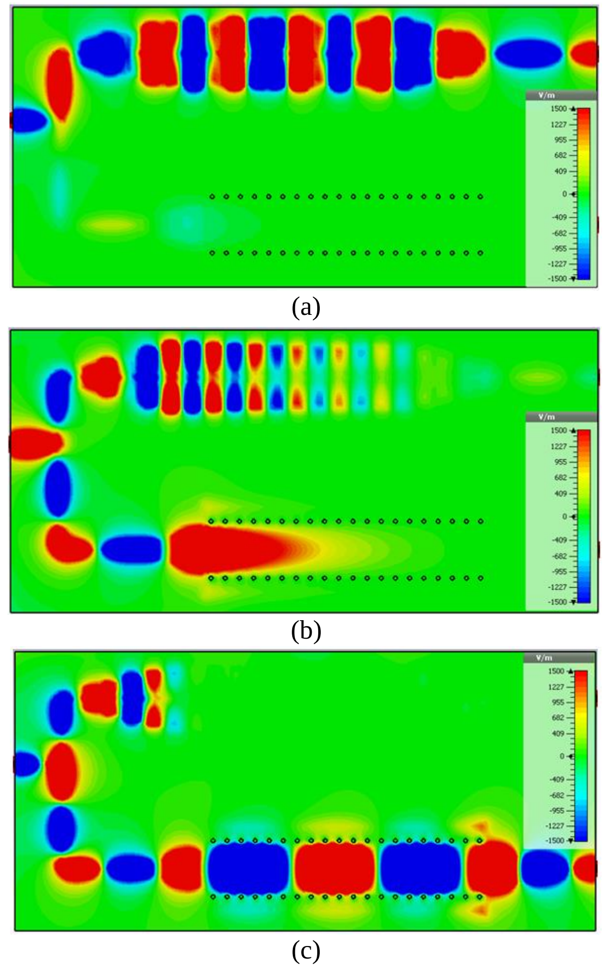


Fig. 10. Simulated near electric field distribution of the proposed diplexer: (a) at center frequency of the down link band (12.225 GHz), (b) at center frequency of the rejection band (15 GHz), and (c) at center frequency of the uplink band (17.825 GHz).

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