A Planar Filtenna Array Implemented by Embedding the Filtering Function into the SIW Power Divider

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Abstract—In this paper, a novelfiltenna (filtering antenna) array is proposed and implemented by embedding the passband filtering function into the power divider feeding network. The proposed array antenna combines filtering, power division and radiation functions according to the classical coupling matrix theory. Besides, the antenna is built in one-layer substrate to achieve low profile and high integration goals. A substrate integrated waveguide (SIW) fourth-order Chebyshev filter is co-designed and embedded into the power divider and the slot radiation elements. The measured impedance matching, gain, and radiation patterns closely agree with simulation results. The center frequency and fractional bandwidth are 24.55GHz and 4.48%, respectively. The measured gain at the center frequency is 7.7dB, and the radiating gain performs a significant filtering characteristic.

I. INTRODUCTION

With the further increase in the requirements for miniaturization and high integration of the transceiver system in the 5G era, the integrated design of the filter and the antenna has become a research hotspot, which called filtenna [1] or filtering antenna. The filtenna not only solves the impedance matching problem when the antenna and the filter are separately designed, but also has important significance for reducing loss and improving radiation efficiency. Different types of filtennas can be designed with different structures and processes [1]-[6]. A filtenna was proposed and implemented by cover a FSS on the aperture of a horn antenna in [1]. A Ku-band omnidirectional planar filtenna was proposed in [2]. A microstrip filtering antenna based on inverted L-type was proposed in [3], in which the microstrip unit is equivalent to a resonator providing radiation function. In [4], a miniaturized filtering antenna based on a microstrip structure is proposed and verified. Dielectric resonator antennas have attracted the attention of scholars because of their low loss [5]. High radiation efficiency slot filtennas can be designed based on the substrate integrated waveguide (SIW) cavity filter due to its high Q-value characteristics [6].

Gain is one of the important performances of the antenna. The gain of the filtering antenna of a single radiating element is low, which is not conducive to improving the signal-to-noise ratio of the system, so it is necessary to design the filtenna array. In [7], a 3-order 4-unit filtering antenna based on microstrip patch is proposed. By designing coupling and power division network, its maximum gain is 9.6dB. Based on the power distribution network of [7], a low sidelobe antenna array with arbitrary power distribution can be realized [8]. In [9], a rectangular waveguide resonator and aperture element are first used to implement a 4×4 filtenna array. In [10], a threestage SIW monopulse filtering antenna array is proposed to realize the sum pattern or difference pattern. However, the gain curve of the antenna is not given, and the multi-layer structure is also not conducive to system integration.

In this paper, a four-order SIW slot filtenna array shown in Fig. 1 is designed and implemented. Each resonator of the filtenna array is coupled by an equivalent inductance window, representing magnetic coupling. The first resonator couples energy into the second and third resonators through two coupling windows. The resonator 6, 7, 8, 9 satisfy both the coupling with the previous-stage resonator and the energy

Fig. 1. (a) Top view, (b) Bottom view of the antenna array (L1=6.25mm, L2=5.74mm, L3=5.5mm, L4=5.69mm, D1=2.96mm, D2=3.16mm, D3=2.7mm, w=6mm, l/f=5.38mm, pa=2.68mm, w/f=0.5mm, pa1=1.26mm)

Fig. 2. (a) Top view, (b) Bottom view, (c) side view of the filter (l1=6.25mm, l2=5.74mm, l3=5.46mm, l4=6.5mm, d1=2.96mm, d2=3.1mm, d3=2.92mm, w=6mm, pa1=1.26mm, pa2=1.24mm).
radiation through the slot. The structure of the proposed filtenna is very compact and easy to integrate for its low profile characteristic.

II. FOUR-OUTPUT FILTER AND FILTERING ANTENNA ARRAY

A. Four-output Filter

The four-order filtenna array with four radiation elements shown in Fig. 1 is based on a four-order Chebyshev one-input four-output filter. The detailed geometry of the proposed filter is illustrated in Fig. 2. This filter is designed in a 0.508mm thick TLY-5 substrate as shown in Fig. 2(c). The dielectric constant and loss tangent of TLY-5 are 2.2 and 0.0009, respectively. The filter consists of 9 resonators, which form four filtering channels. Each output of the filter has a four-order filter output characteristic. The input and output of the filter are fed by a coaxial line. The position of the coaxial line determines the coupling between the cavity and the source and load. The SMP connector is coupled to the resonator by drilling a via with a diameter of 0.55mm in substrate and etching a circle with a diameter of 1.8mm at the bottom of the filter. The topology of the four-output filter proposed in this paper is shown in the Fig. 3(b), which can be extracted from a traditional cascaded one-output filter shown in Fig. 3(a). For the topology shown in Fig. 3(a), the coupling coefficient between each cavity $m_{mn}$ and external quality factor $q_{en}$ can be obtained according to the Chebyshev filter coupling theory [11]. For the filter whose objective center frequency, fractional bandwidth (FBW) and in-band return loss are 24.5 GHz, 4.08% and -25dB, then

$$m_{12}=\frac{1}{\sqrt{1+g1g2}}=1.0409$$

$$m_{23}=\frac{1}{\sqrt{1+g2g3}}=0.7715$$

$$m_{34}=\frac{1}{\sqrt{1+g3g4}}=1.0409$$

$$q_{e1}=q_{e4}=g0g1=0.7533$$

$$Q_{e1}=Q_{e4}=q_{e1}/FBW=18.46.$$  \(5\)

For the topology shown in Fig. 3(b), node 1 and nodes 2, 3, node 4 and nodes 6, 7, node 5 and nodes 8, 9 all acts as an equally divided power divider. To ensure the filtering characteristic is unchanged, we have [11]

$$m_{12}=m_{13}=\frac{1}{\sqrt{1+g1g2}}=0.736$$

$$m_{46}=m_{47}=m_{58}=m_{59}=\frac{1}{\sqrt{1+g3g4}}=0.736$$

$$q_{e6}=q_{e7}=q_{e6}=q_{e9}=g0g1=0.7533.$$  \(8\)

The theoretical response of the two topologies is plotted in Fig. 4 according to (9) and (10) using Matlab. It can be observed that the transmission coefficient of the four-output filter is 6dB lower than one-output filter, while the reflection coefficients are completely coincident.

$$S_{11}=1-\frac{q_{e1}}{q_{en}}[A]_{11}$$

$$S_{n1}=2\frac{1}{\sqrt{q_{e1}q_{en}}}[A]_{11}^{-1}.$$  \(10\)

The dimensions of the four-output filter can be estimated using the coupling coefficient and external quality factor obtained above. The frequency response is optimized by using Ansoft High Frequency Structure (HFSS). The filter dimensions are shown in Fig. 1. Fig. 5 shows the simulation and ideal response of the 4-order 4-output filter. It can be observed that the maximum transmission coefficient obtained by the simulation is -6.8 dB, which is 0.8 dB lower than the ideal value. This result can be due to the dielectric loss.

B. Filtenna Array

The four-order filtenna array based on a four-order four output filter is implemented in this section. The only difference between filtenna and filter is each output port of the filter is replaced by a slot antenna from Fig. 1 and Fig. 2. For the purpose that the slot antenna is equivalent to the output port of the filter, the radiation quality factor of the radiator in the filtenna has to be identical to the external quality factor of the last resonator in the filter. At the same time, the last resonator need resonates at the center frequency to ensure same frequency response.

Using the approach in [4] to extract the radiation quality factor of the radiator, a transverse slot in the broad wall of a waveguide can be equivalent to a series resistance. The slot parameters can be obtained when the radiation quality factor is 18.46 using HFSS. The final slot parameter is $L_f = 5.38\,\text{mm}, wf = 0.5\,\text{mm}, pa = 2.68\,\text{mm}$.
The simulated center frequency and bandwidth of the filtering antenna are 24.5 GHz and 4.08%, respectively, as shown in Fig. 7. Return losses higher than −16 dB are achieved in the passband and the gain has a maximum value in center frequency of 9.6 dB. The radiation gain performs a good selection characteristics and out-of-band rejection.

III. MEASUREMENT AND DISCUSSION

Prototype of the filtenna is fabricated and measured. The photo of the prototype is shown in Fig. 6. The return loss is measured using SMP connector and network analyzer.

The measured center frequency and fractional bandwidth are 24.55 GHz and 4.48%, respectively, as shown in Fig. 7. The measured return loss is better than 10 dB across the passband. The measured maximum gain is 7.7 dB at the center frequency, which is 1.9 dB lower than simulated value. This may due to connector loss and fabrication tolerances. The measured radiation gain performs a significant filtering characteristic.

The measured radiation patterns are closely agree with simulation results at the center frequency in both H-plane and E-plane. The sidelobe level of H-plane is less than -13.1 dB.

IV. CONCLUSIONS

A novel filtenna array based on substrate integrated waveguide structure is proposed, fabricated and measured. It has been shown the center frequency and fractional bandwidth are 24.55 GHz and 4.48%, respectively. The realized gain measured of the filtering antenna performs significant filtering characteristic with a maximum gain of 7.7 dB.

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