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Two-stage Waveguide Bandpass Filter Composed of Circular Dielectric Resonators

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Abstract

In this paper, the design of two-stage waveguide bandpass filter (BPF) is investigated numerically and experimentally. The filter which is composed of 2 circular dielectric resonators (CDR) with high permittivity is proposed to operate at the dominant mode of TE_{11} center frequency around 1GHz for microwave communication. Due to the use of CDR, the filter is expected to have better quality factor compared to lumped elements-based BPF. Each dielectric resonator has relative permittivity of 140 with the diameter of 13.5mm and the height of 6.7mm. The filter is excited using circular patches which are deployed on FR4 Epoxy dielectric substrates with the relative permittivity of 4.3 and the thickness of 1.6mm. From the measured result, it shows that the proposed filter has the center frequency of 1.12GHz, the 3dB working bandwidth of 200MHz ranges from 1.01GHz to 1.21GHz, and the maximum insertion loss at passband area of 1.87dB.

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Keywords: circular dielectric resonator; high relative permittivity; resonant mode; two-stage BPF.

1. Introduction

In earlier times, the development of BPF or other type of filters is usually established by use of some approach which is based on the concept of electric field and magnetic field interaction. Commonly, the concept is

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implemented through lumped elements such as capacitors and inductors, and is carried out by adopting transmission line theory in the analysis. In accordance with some specification in particular for microwave communication, the filter is required to be able in handling of higher frequency operation with low loss transmission. Here, to implement filters workable for such frequency operation as well as for microwave region, some design which are based on distributed elements instead of lumped elements have been approached and realized using coaxial line, stripline, microstrip line, waveguide, and dielectric resonator [1-3].

As the supplement of requirements above, the filters should also be designed to be lighter in weight, compacter in size, smaller insertion loss and sharper selectivity especially in the passbands area. In the design of BPF, some investigations have been actually conducted numerically and experimentally [4-7], however, there has always been a fundamental challenge to achieve a sort of trade-off between the parameters of filter including insertion loss, return loss, quality factor and bandwidth. Furthermore, another approach to design BPF using high permittivity circular dielectric resonators (CDR) coupled with microstrip lines for the excitation has also been reported recently [8-9]. In latter, the design has demonstrated a narrowband BPF with fractional bandwidth of 2.9% in which the CDR have been introduced to produce lower insertion loss in passband area.

2. Design overview of two-stage waveguide bandpass filter

2.1. CDR and excitation circuit

In the design of two-stage waveguide bandpass filter, as shown in Fig. 1, the used circular dielectric resonators (CDRs) have relative permittivity of 140 with the diameter ($d$) of 13.5mm and the height ($L$) of 6.7mm. Based on Eq. (1) [10], the resonant frequency of CDR (in GHz) can be theoretically approximated.

$$ f = \frac{68}{d} \sqrt{\varepsilon_r} \left( \frac{d}{2L} + 3.45 \right) $$

where $d$, $\varepsilon_r$, and $L$ are diameter of CDR in mm, relative permittivity of CDR, and height of CDR in mm, respectively. By using the parameter value of CDR above, the resonant frequency of CDR for the dominant mode is 1.898GHz. Since the resonant frequency of CDR is far from the desired center frequency of design filter, i.e. around 1GHz, therefore 2 CDRs which are put in inside of circular waveguide should be laid somehow close each other to gain the optimum coupling. Here, after conducting some parametrical studies through the simulation which are also verified using theoretical approaches, the optimum coupling is obtained when the distance between the CDRs is 1.4mm.

Next, to obtain passband characteristic of proposed filter at the dominant mode of $TE_{11}$, the excitation port is provided by employing 2 circular patches for CDR as illustrated in Fig. 2. The circular patches have the radius ($r$) of 6.3mm which are implemented on FR4 Epoxy dielectric substrates with the relative permittivity of 4.3 and the thickness ($t$) of 1.6mm. The resonant frequency of circular patch exciter as well as its characteristics can be treated and analyzed using the circular patch antenna approximation. To determine the resonant frequency of circular patch for the dominant mode of $TE_{11}$, it can be calculated using Eq. (2) as follow.
\[ f_{11} = \frac{c}{2\pi r \sqrt{\varepsilon_r}} x_{11}' \]  

where \( c \), \( r \), \( \varepsilon_r \), and \( x_{11}' \) are speed of light in vacuum \((3 \times 10^8 \text{ m/s})\), radius of circular patch in meter, relative permittivity of dielectric substrate, and root of Bessel function for TE\(_{11}\), respectively. The value of \( x_{11}' \) for TE\(_{11}\) mode is 1.842. Whilst for other TE modes, the values of \( x_{11}' \) are summarized in Table 1. Based on the parameter value of circular patch above, the resonant frequency of each circular patch for the dominant mode of TE\(_{11}\) is 6.732GHz. Each circular patch is fed by using 50Ω SMA connector in which the probe of connector is connected to the circular patch. The probe is not connected to at the center of circular patch but rather being shifted 5mm from the center of circular patch in order to obtain the better impedance matching.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( x_{11}' ) for TE(_{11}) mode</th>
<th>( x_{n2}' )</th>
<th>( x_{n3}' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.832</td>
<td>7.016</td>
<td>10.174</td>
</tr>
<tr>
<td>1</td>
<td>1.842</td>
<td>5.331</td>
<td>8.536</td>
</tr>
<tr>
<td>2</td>
<td>3.054</td>
<td>6.706</td>
<td>9.970</td>
</tr>
</tbody>
</table>

2.2. Two-stage waveguide BPF

As illustrated in Fig. 3, the proposed two stage waveguide bandpass filter (BPF) is constructed of 2 circular dielectric resonators (CDRs). As discussed above, each CDR has relative permittivity of 140 with the diameter of 13.5mm and the height of 6.7mm. The port excitations are designed by use of circular patch deployed on 1.6mm thick FR4 Epoxy dielectric substrates with the relative permittivity of 4.3. Each circular patch is then fed by using a 50Ω SMA connector. Due to the probe position of SMA connector, the circular patch is excited to work at TE\(_{11}\) mode. To obtain the characteristic response of proposed design, the filter is then numerically characterized where the result is plotted in Fig. 4. From the numerical result, it shows that the proposed filter has the center frequency of 1.15GHz, the 3dB working bandwidth of 60MHz ranges from 1.11GHz to 1.17GHz, or the fractional simulated bandwidth is 6.1%. Hence, the maximum insertion loss and minimum return loss at passband area is 1.33dB and 20.56dB, respectively. It should be noted that the narrow band of working bandwidth is mostly affected by the high \( Q \) factor of CDR used in the design, where the bandwidth is inversely proportional to the \( Q \) factor.
3. Hardware realization and characterization

To verify the numerical characterization, a hardware realization of two-stage waveguide BPF composed of 2 CDRs is carried out based on the numerical design. Figure 5 shows pictures of realized two-stage BPF. To be easier in the realization process, the used waveguide has an outside rectangular shaped but circular shaped in inside of waveguide. Actually the important shape for the filter realization is the inside one in which the shape will fit for circular dielectric resonators (CDRs). Hence the circular patch port excitation is realized using FR4 Epoxy dielectric substrate through wet etching technique to be connected with the SMA connector. To obtain the gap of 1.4mm between 2 CDRs, a spacer made of styrofoam is placed tightly between CDRs. Here, the styrofoam is used since it has the parameters, i.e. permeability and permittivity, almost similar to the free space. After inserting CDR into the waveguide, the excitations port are fitted at both ends of waveguide to be characterized through a Vector Network Analyzer.

The experimental characterization result for realized filter is depicted in Fig. 6 with the numerical characterization result is plotted together for comparison. It is seen that the realized filter has center frequencies of 1.12GHz and the 3dB working bandwidth of 200MHz ranges from 1.01GHz to 1.21GHz, or the fractional measured bandwidth is 17.8%. It should be noted that the measured center frequency is shifted lower 30MHz than the simulated one, while the 3dB working bandwidth is larger more than 300% from the simulated one. This is possibly evoked by the CDR used for measurement which probably has the lower $Q$ factor to the one which is used in the simulation affecting the wider of working bandwidth. From the experimental characterization result, it is also shown that the maximum insertion loss and minimum return loss at passband area is 1.87dB and 14.3dB, respectively, in which these values are worse than the numerical characterization results.

![Fig. 5. Realization of two-stage waveguide BPF composed of 2 CDRs](image1)

![Fig. 6. Simulated and measured results of two-stage waveguide BPF](image2)

4. Conclusion

The design and characterization of two-stage waveguide bandpass filter composed of 2 circular dielectric resonators with high permittivity has been demonstrated numerically and experimentally. The filter was excited using circular patches deployed on FR4 Epoxy dielectric substrate to generate the dominant mode of TE$_{11}$. From the experimental characterization results, it has been demonstrated that the realized filter has the center frequency of 1.12GHz, the working bandwidth of 200MHz ranges from 1.01GHz to 1.21GHz, and the maximum insertion loss at passband area of 1.87dB. Although the experimental characterization have shown the difference result compared to the numerical ones especially in term of bandwidth due to the discrepancy of $Q$ factor, however the realized filter has shown an acceptable performance and could be applied for microwave communication.
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References