High-Q Whispering Gallery Mode Dielectric Resonator Bandpass Filter with Microstrip Line Coupling and Photonic Bandgap Mode-Suppression

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***Abstract*—We describe a novel bandpass filter based on using Whispering Gallery (WG) modes in high-density dielectric resonators (DR). Microstrip line mode-coupling and photonic bandgap (PBG) suppression techniques are also features of this design. Based on this approach, we demonstrate a filter with center frequency of 13.7 GHz, Q of 2000, insertion loss of 7 dB, and attenuation of 30 dB.**

***Index Terms*—Bandpass filter, dielectric resonator, mode suppression, photonic bandgap.**

I. Introduction

THE NEED for high-Q, narrow passband filters stems from the requirements of the emerging high data rate communications systems. Future communications systems are expected to utilize wireless and optical techniques that rely on rf frequency in excess of 10 GHz, and approaching 90 GHz for many planned applications. These systems can offer even further capacity if they operate with high channel density. Such requirements point to the need for components, including filters, operating at high frequencies with Q's in excess of a few thousand. Currently, the most widely used filters with above parameters are tuned cavity filters, which are nevertheless bulky, and ill suited for many applications. In this letter, we will describe a novel design that has the potential to meet the requirements of the emerging high data rate systems, in a package that is small and efficient.

High order whispering gallery (WG) mode dielectric resonators (DR's) are attractive for filter applications, since they can generally have a small size, and high Q's at high frequency [1]–[3]. One of the challenges associated with designing filters based on these resonators, nevertheless, is efficient coupling to the high order modes. Coupling schemes conventionally used with WG mode DR's include loop, waveguide, and microstrip line coupling. Because of its amenability to integration, the microstrip line coupling is the preferred approach, but the wide bandwith associated with microstrip lines represents an undesirable feature. This is because line coupling makes the selection of a particular mode from amongst the usually large number of WG modes of the DR very difficult. In applications where high-Q single frequency response is required, e.g., single frequency bandpass filtering, and mode selecting elements such as thin metal plates and lines have to be implemented with the DR [4], [5]. However, these elements typically can only partially suppress the spurious modes with a relatively high Q penalty, and for small size resonators operating at high frequencies, these techniques become impractical.

We have approached the problem of mode selection of the WG DR filters by combining these elements with photonic bandgap (PBG) structures [9]. These structures have attracted much interest recently in a variety of optics, acoustics, and microwave applications [6]. They are essentially periodic arrays which interferometrically suppress selected frequencies, while passing others. In this letter, we describe a new WG resonator bandpass filter with PBG mode suppression. Our experiments show an efficient suppression of spurious modes close to the frequency of interest for a high-Q single frequency filter operation.

II. Device Description

The dielectric WG resonator filter and its coupling configuration as used in our experiments is shown in Fig. 1. A high-density cylindrical DR with dielectric constant 30, diameter 8.75 mm, and height 4.28 mm is mounted on a low loss dielectric substrate with dielectric constant 2.2. The unloaded Q of this DR disk is about 15 000 at 10 GHz, and the substrate has dissipation factor (loss tangent) 9×10^{-5} at 10 GHz. The minimum thickness (h) of the substrate without degrading the Q of DR is calculated to be 0.5 mm. Two 50 Ω copper striplines with 1.5 mm width (w) were fabricated on the top of the substrate and a DR was placed between the two transmission lines to couple energy from one microstrip line to the other. Each microstrip line was terminated with a high-frequency 50 Ω termination to reduce reflection from the end.

In practice, there is a tradeoff between the insertion loss and the loaded-Q of the DR, and is determined by the relative position of the DR disk between the microstrip lines. Instead of using conventional straight microstrip lines, we used curved strip lines for both mode excitation and coupling. This allows a convenient way to adjust the position of the DR disk between strip-lines, and enables determination of an optimum position for both high loaded-Q and low insertion loss experimentally.

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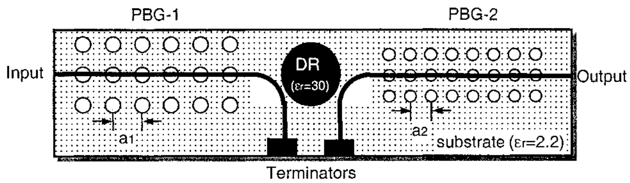

Fig. 1. Filter structure of microstrip line with DR and PBG combination. Circles of PBG structures are etched on the bottom side of substrate.

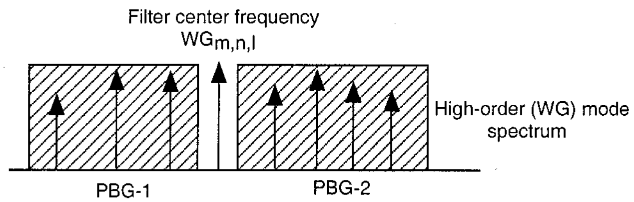

Fig. 2. Spectral diagram showing the WG mode suppression by using PBG structure.

The effective dielectric constant which will be used later for the computation of center stop-band frequency of PBG structure is related to the substrate dielectric constant $\varepsilon_r (= 2.2)$ and microstrip line structure given above as

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \sqrt{\frac{w}{w + 12h}} \tag{1}$$

where the dispersion and the thickness of strip lines are ignored. For the particular case shown in Fig. 1, ε_{eff} equals to 1.87.

Following the process described in [6], three rows of periodic circles were etched on the ground plane (the bottom side of the substrate), along the strip lines located on the top side of the substrate to form the band gap structure. We found experimentally that the depth of the stop band is proportional to the number of grids of the structure, and inversely proportional to the thickness of dielectric substrate. Also, the width of the stop band is proportional to the size of circles of the grid, and inversely proportional to the thickness of dielectric substrate. Therefore, to make band gaps deep and wide, a large number of circles with large size, and a thin substrate are required.

As shown in Fig. 1, the structure on the left (PBG-1) has six grids with a periodicity (a_1) of 10 mm and a circle diameter of 3.75 mm, corresponding to a measured center stop-band frequency of 10.5 GHz. The structure on the right side (PBG-2) consists of eight grids with a periodicity (a_2) of 6.25 mm, a circle diameter of 2.5 mm, and a measured center stop-band frequency of 17 GHz. Theoretically, the center stop-band frequency f_i of PBG-i can be calculated as

$$f_i = \frac{c}{2\sqrt{\varepsilon_{\text{eff}}}\, a_i} \tag{2}$$

where c is the speed of light in free space and ε_{eff} is the effective dielectric constant given in (1).

From (2), the calculated center stop-band frequencies are 10.96 GHz for PBG-1 and 17.55 GHz for PBG-2. Therefore, the simple equation in (2) can predict the center frequency of PBG structure to an accuracy of 5%.

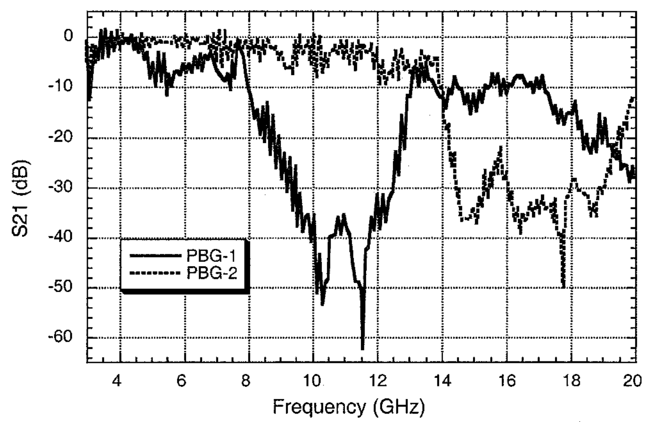

Fig. 3. Measured transmission (S_{21}) of two frequency bands of PBG structures.

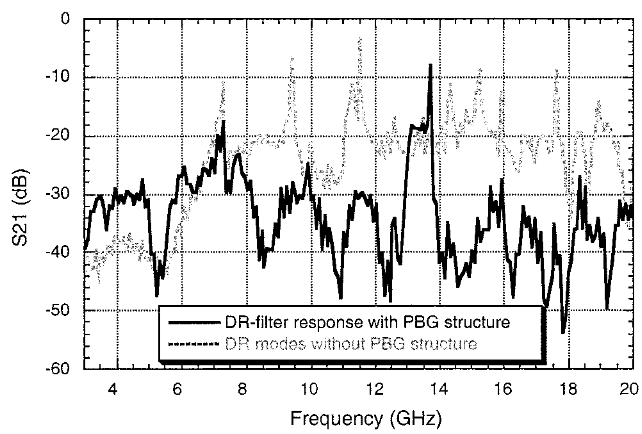

Fig. 4. Measured transmission (S_{21}) of proposed high-Q filter which has center frequency of 13.7 GHz. Dotted line shows the S_{21} of the same DR-microstrip-line-coupling structure without PBG's.

Fig. 2 illustrates two PBG structures used to suppress the spurious modes around the intended transmission peak. In the absence of PBG structures, many high order WG modes, together with the desired mode, are coupled from the input microstrip line to the output microstrip line. With properly designed PBG structures underneath the corresponding strip lines, spurious modes around the intended resonant frequency (the center frequency of the filter) can be suppressed significantly. From (2), the center frequency of the filter should satisfy the following spectral relation:

$$\frac{c}{2\sqrt{\varepsilon_{\text{eff}}}\, a_1} + \frac{BW_1}{2} < f_{m,n,l} < \frac{c}{2\sqrt{\varepsilon_{\text{eff}}}\, a_2} - \frac{BW_2}{2} \tag{3}$$

where BW is the width of PBG stop-band, and m, n, l are azimuthal, radial and axial mode number of a particular WG mode in cylindrical resonator.

III. Measurement Results and Discussion

The bandgap (bandreject) effect of two PBG structures was observed using a commercial network analyzer. The experimentally measured results of S_{21} parameters of these PBG's are shown in Fig. 3. PBG-1 has center frequency of 10.5 GHz and

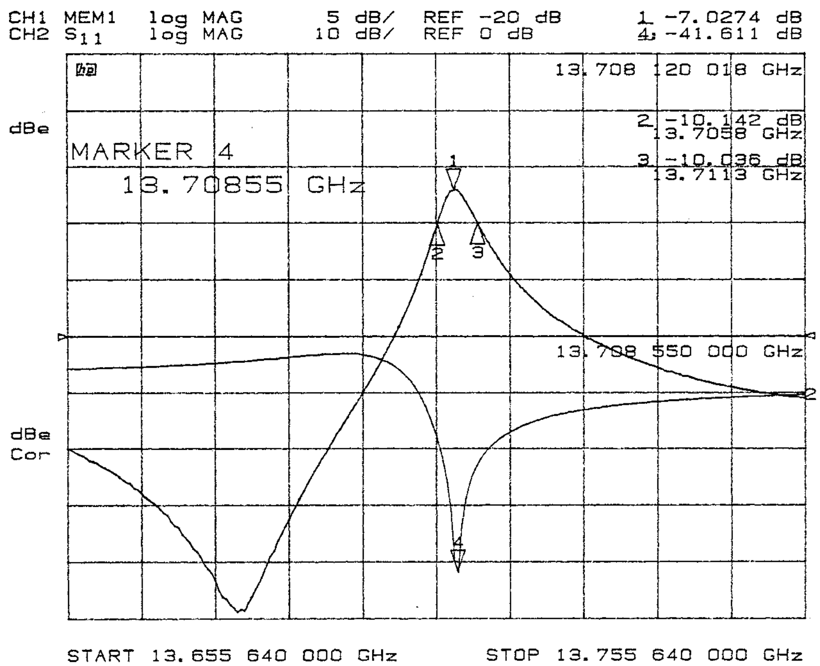

Fig. 5. S_{21} and S_{11} parameters of proposed filter with 100 MHz span.

5 GHz bandwidth, and PBG-2 has center frequency of 17 GHz and 6 GHz bandwidth. The depth of stop-band center frequency for both structures is about 40 dB.

Fig. 4 shows a comparison between filter S_{21} response with and without PBG structures. Suppression of spurious modes around the mode of 13.7 GHz which is center frequency of proposed bandpass filter can be more than 20 dB, and an extremely large free spectra range (more than 12 GHz) is obtained. This result is significant comparing to the metal spacer technique [4] which has more complicated structure with 5–20 dB spurious mode suppression and much smaller free spectra range.

Fig. 5 shows the filter S_{21} response with 100 MHz span. The 3 dB-bandwidth is 7 MHz (quality factor is about 2000), insertion loss is about 7 dB and attenuation is about 30 dB. The relatively high insertion loss is caused by loss of microstrip lines at high frequencies, and this can be improved by using higher density substrate.

There are many published studies on the computation of resonant frequencies of cylindrical DR by using full-wave analysis and finite element technique [1], [2], [7]. The bandgap of PBG structure also can be calculated by FDTD [6]. Therefore, the proposed filter can be easily designed by these existing techniques for any frequency bands and other requirements.

IV. Conclusion

A high-Q filter with combination of Whispering Gallery modes in high-density DRs, microstrip line mode-coupling and PBG suppression techniques has been proposed and demonstrated experimentally. This proposed filter provides deep attenuation and spurious-free response at 13.7 GHz without any effecting of Q-factor. With existing computation techniques, this filter can be designed for any frequency bands.

The techniques described in this letter also can be expected to control modes in the WG-mode Sapphire resonators to achieve extremely low phase noise oscillators operating at higher frequencies [8].

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