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Low Dielectric Loss Ceramics in the $ZnAl_2O_4$–TiO_2 System as a τ_f Compensator

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In the last few decades, the microwave-based wireless communications industry has been revolutionized by using the ceramic dielectric materials to reduce the size and the cost of components in circuit systems due to their unique electrical properties. In particular, size reduction is mainly a result from the use of high-dielectric-constant material since the wavelength (λ) in dielectrics is inversely proportional to $\sqrt{\varepsilon_r}$ according to the relation $\lambda = \lambda_o/\sqrt{\varepsilon_r}$, where λ_o is the wavelength in vacuum. However, as the frequency of interest is extended from ISM (industrial, scientific and medical) bands to millimeter wave range, materials with high dielectric constant tend to become a less of interest. Consequently, high quality factor together with low dielectric constant would play a more prominent role instead, since high quality factor can significantly reduce the dielectric loss and low dielectric constant which allows a fast time for electronic signal transition at ultra high frequencies. Zero τ_f is also one of the major requirements for dielectric materials to be utilized as a frequency-stable passive component. The most convenient and promising way to achieve a zero τ_f is to combine two compounds having negative and positive τ_f values to form a solid solution or mixed phases. However, high dielectric constant materials exhibit high dielectric loss (low $Qu\times f$ value) and large positive τ_f, while low loss ceramics are usually accompanied by low ε_r value and negative τ_f. Consequently, it becomes a trade off problem when mixing two compounds having opposite τ_f values. For instance, mixing $MgTiO_3$ (ε_r = 17, $Qu\times f$ ~160,000 GHz, τ_f ~ -50 ppm/oC) and $CaTiO_3$ (ε_r = 170, $Qu\times f$ ~3,600 GHz, τ_f ~ 800 ppm/oC) would lead to a compromised combination of dielectric properties (ε_r = 21, $Qu\times f$ ~56,000 GHz, τ_f ~ 0 ppm/oC) for $0.95MgTiO_3$-$0.05CaTiO_3$.

Instead of searching for a low dielectric constant material, we seek to develop a dielectric having low ε_r, high $Qu\times f$, and particularly, a large positive τ_f, so that it can be act simultaneously as a compensator for τ_f to avoid encountering of the aforementioned trade off problem. Therefore, the dielectric properties of $ZnAl_2O_4$–TiO_2 system were closely investigated and discussed in terms of the compositional ratio, the densification and the sintering temperature of the specimens. The phases of $ZnAl_2O_4$ and TiO_2 co-exist with each other and form a two-phase system, which is confirmed by the XRD patterns and the EDS analysis. The microwave dielectric properties of the specimens are strongly related to the sintering temperature, the density, and the mole ratio of $ZnAl_2O_4/TiO_2$. Sintering temperature of specimen can be effectively lowered by increasing TiO_2 content. The $Qu\times f$ values of the ceramics could be significantly boosted by adding appropriate amount of TiO_2 and sintered at a suitable temperature. Consequently, a very high $Qu\times f$ of 277,000 GHz associated with a ε of 25.2 and a large τ_f of 177 ppm/oC are obtained using $0.5ZnAl_2O_4$-$0.5TiO_2$ ceramics at 1390oC/4 h. These unique properties can be utilized as a τ_f compensator for dielectrics which would require extremely low loss.

Table 1 Microwave dielectric properties of ($0.5ZnAl_2O_4$–$0.5TiO_2$)-based ceramic system

No.	Composition	ε_r	$Qu\times f$(GHz)	τ_f(ppm/^{o}C)
1	$MgTiO_3$	17	160,000	-50
		18	140,000	-50
2	$Mg_4Nb_2O_9$	12.4	192,000	-70.5
		11	210,000	-70
3	($0.5ZnAl_2O_4$–$0.5TiO_2$)	25.2	277,000	177
4	$0.23MgTiO_3$–$0.77(0.5ZnAl_2O_4$–$0.5TiO_2)$ at 1360^{o}C/4 h	18.7	190,000	-1.8
5	$0.47Mg_4Nb_2O_9$–$0.53(0.5ZnAl_2O_4$–$0.5TiO_2)$ at 1390^{o}C/4 h	13.4	210,000	1.8

To verify the performance of the proposed material as a compensator for τ_f, $MgTiO_3$ and $Mg_4Nb_2O_9$ were individually mixed with the $0.5ZnAl_2O_4$–$0.5TiO_2$ ceramics to achieve dielectrics with low ε_r, high $Qu\times f$, and nearly zero τ_f. Table 1 illustrates the microwave dielectric properties of the ceramic mixtures. Consequently, τ_f of specimen can be effectively compensated while still retaining an extremely high $Qu\times f$ value. An additional phase was not detected for these compositions. In addition, a circle dual-mode microstrip bandpass filter was designed and fabricated on different dielectric substrates, namely, FR4, alumina and ($MgTiO_3$)–($0.5ZnAl_2O_4$–$0.5TiO_2$). Fig. 1 shows the physical layout and the fabricated filters designed with a central frequency of 2.5 GHz, and the measurement results are illustrated in Table 2. In comparison with FR4 and alumina, the filter using the proposed dielectric not only shows a tremendous reduction in the insertion loss but also demonstrates a considerable reduction in its size.

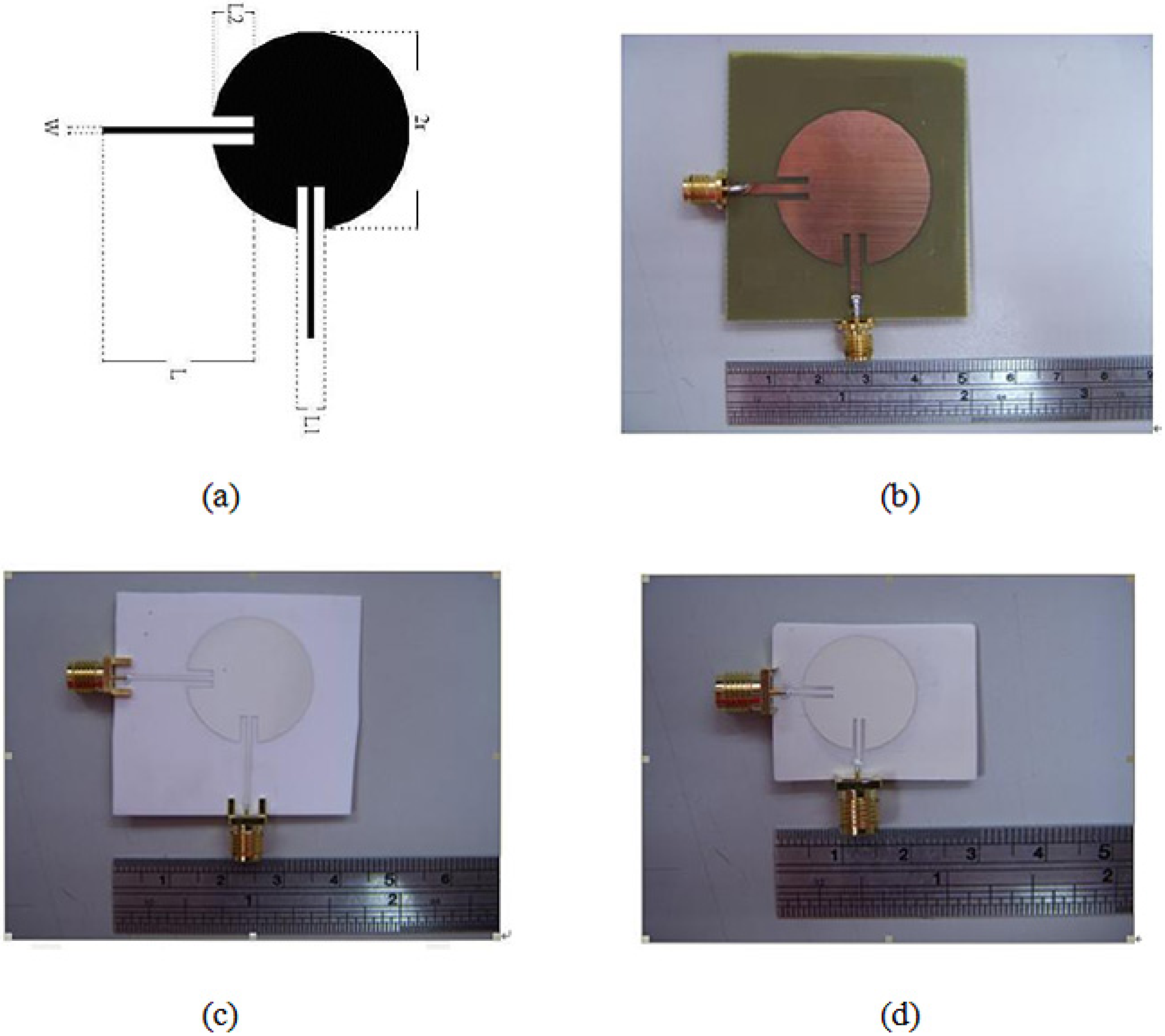

Fig. 1 The (a) physical layout of the designed circle dual-mode microstrip bandpass filter with a central frequency of 2.5 GHz, and fabricated ones on substrates using (b) FR4, (c) alumina, and (d) presented dielectric.

Table 2 Measurement results of the bandpass filters using different dielectrics

Dielectrics	FR4	Alumina	Presented #4
ε_r	4.5	9.7	18.7
Tanδ	0.015	0.0001	0.000013
Central freq. (GHz)	2.52	2.48	2.55
Insertion loss (dB)	-3.8	-2.5	-0.8
Return loss (dB)	-27	-31	-37
Bandwidth (MHz)	220	200	205
Size (mm^2)	632	400	149