Polymer–Ceramic Composites for Microwave Applications: Fabrication and Performance Assessment

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***Abstract*—We present a novel technique to fabricate conformal and pliable substrates for microwave applications including systems-on-package. The produced materials are fabricated by combining ceramic powders with polymers to generate a high-contrast substrate that is concurrently pliable (bendable). Several such polymer–ceramic substrates are fabricated and used to examine the performance of a patch antenna and a coupled line filter. This paper presents the substrate mixing method while measurements are given to evaluate the loss performance of the substrates. Overall, the fabricated composites lead to flexible substrates with a permittivity of up to $\varepsilon_r = 20$ and sufficiently low loss.**

***Index Terms*—Control of dielectric properties, high-contrast substrates, particle dispersion technique, pliable substrates, system-on-package (SoP).**

I. Introduction

MANY COMPLEX, mobile structures (aircrafts, ships, and automobiles) require conformal antennas for radio communication. This requirement can be particularly challenging for small platforms since a large antenna is needed at these frequencies. Concurrent requirements for greater bandwidth and multifunctionality imply an even greater need for conformality. Existing conformal antennas are still printed on rigid laminate substrates with curved shapes, making them expensive and cumbersome, if not impractical, to manufacture and, hence, not applicable for such platforms. Further, an increasing demand for integration of antennas with radio-frequency (RF) front-end circuits makes use of such high-contrast substrates very attractive since they also allow for miniaturization.

Polymers are rapidly becoming important among materials for microwave and electronic applications whether used in pure form or combined with ceramic powders. For example, in optoelectronics, polymers have been used to produce mechanically flexible "electronic paper" [1] and high-efficiency light-emitting diodes [2]. Liquid crystal polymers (LCPs) have been proposed for system-on-package (SoP) applications, displaying attractive properties like low loss, low water absorption, and low cost [3]. As a result, the LCPs have been promoted as a less expensive application than the system-on-chip (SoC) technology [4]. For SoPs, a three-dimensional (3-D) fabrication capability is needed, and this is done via stereolithography where traditional lithography is applied to fabricate complex microwave components [5]. Among example RF applications already reported, we note the use of an electro-optic polymer in [6] to design photonic RF arrays. In [7], polymer–ceramic composites were proposed as substrate materials for a scanning antenna, and, in [8] and [9], polymer–ceramic mixtures were used for thin-film capacitors. What is important to note about polymers is that: 1) though they are not intrinsically functional, they can be doped and made functional and 2) their "soft" or pliable nature (unlike crystalline materials) enables flexible free-standing substrates in a variety of different shapes.

In this paper, we propose (for the first time, to the best of our knowledge) ceramic-reinforced elastic polymer composite substrates for truly conformal microwave applications suitable for a wide range of operating frequencies, i.e., 100 MHz–20 GHz. A key advantage of the polymer–ceramic mixtures is the capability to specify a range of high-contrast substrates by controlling the ceramic mixture. The ceramic is introduced into the polymer via a particle dispersion process, and its inherent elasticity is maintained provided the ceramic powder mixture is kept below a certain percentage, e.g., 30%–40%. Nevertheless, this percentage level of mixtures allows for a significant range of substrate dielectric constants which can also vary within the substrate for texturing or other material design applications [10].

The practicality of the proposed polymer–ceramic substrates presents us with other benefits, including the capability for metallic inclusions within the substrate with no limitation on substrate thickness, whichis typically not the case with low-temperature co-fired ceramic (LTCC) technology [11], [12]. Additionally, SoP integration applications can be considered. Moreover, the proposed mixing method is simple and avoids expensive machinery needed for composite fabrication. It is being carried out at room temperature, the complete procedure takes about a day, and it avoids issues often encountered with hard ceramic substrates (e.g., thermal mismatches or cracks).

In this paper, we use composite substrates created by combining polydimethylsiloxane (PDMS) polymers from Dow Corning with various ceramic powders, namely barium titanate (BT-$BaTiO_3$), Mg-Ca-Ti (MCT) from Trans-Tech Inc., and Bi-Ba-Nd-Titanate (BBNT) from Ferro Corporation. The dielectric properties of the fabricated substrates are measured using an Agilent impedance material analyzer, and measurements are verified by manufacturing and testing simple patch

Manuscript received January 6, 2006; revised July 5, 2006.
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Digital Object Identifier 10.1109/TMTT.2006.885887

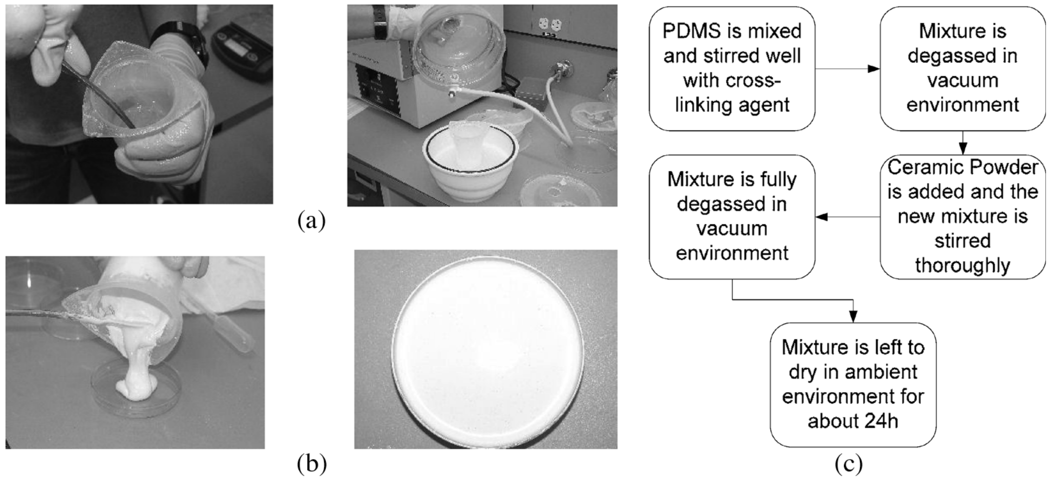


Fig. 1. Fabrication procedure for the proposed substrates. From left to right: (a) PDMS is prepared by mixing silicone gel with a crossing agent, stirred and then degassed to remove surface bubbles; (b) ceramic is added, mixture is stirred, poured into containers, degassed, and left to dry; and (c) schematic representation of the procedure.

antennas on the polymer–ceramic substrates. A coupled line filter is also designed and measured to ensure low-loss performance. Both the filter and patch are measured after bending at various angles to demonstrate the flexibility of the substrate. In the next sections, we begin by presenting fabrication processes followed by the characterization of the substrates performance and suggested use for antennas and filter applications.

II. Materials and Fabrication Methods

A. Materials

Among available polymer materials, we chose to work with silicone primarily due to its highly desired elastic behavior. PDMS is the most widely used silicone-based organic polymer and is known for its unusual rheological/flow properties: it is nonflammable, water- and chemical-resistant, and stable at high temperature. PDMS has been extensively used in MEMS technology and for the production of various probes and chips in medical applications [13].

Among the various shades of commercial ceramic powders, namely LTCC and high-temperature co-fired ceramics (HTCC), we chose to work with BT-, BBNT-, and MCT-type powders because of their wide range of available dielectric constants. BT has been widely employed in capacitor technology due to its ferroelectric properties [14], [15]. It is usually mixed with polymers [8], [9], [16] and demonstrates a wide range of attainable dielectric permittivity (from a few tens to a few thousands) values depending on its chemical form, grain size, environment temperature, and added dopants [17]. BBNT falls into the LTCC group of ceramic powders. It displays a dielectric permittivity of up to 100 [10]. The MCT powder is an HTCC and is commercially available in different dielectric shades from 20 to 140.

B. Fabrication Procedure

The proposed particle dispersion process is particularly suited for pliable substrates. Unlike other techniques, it is implemented at ambient temperatures. The process starts with the preparation of T2 Silastic PDMS by adding one part (mass) of a cross-linking agent to ten parts (mass) of silicone gel. The resulting silicone gel is mixed thoroughly and placed into a vacuum chamber where excessive gas is removed by venting the surface bubbles within the prepared gel. Next, the desired amount of ceramic powder is added to the degassed silicone gel and is again mixed thoroughly. The resulting ceramic–polymer slurry mixture is poured into a plastic container (of the desired shape). Degassing of the resulting mixture is then done by placing the containers into a vented vacuum chamber as done for the pure silicone gel. This process is the most tedious step and plays a critical role to achieving homogenous ceramic-reinforced polymer substrates. An average degassing time for a dish (of average thickness 6 mm and average diameter 30 mm, filled with 20% ceramic) is approximately 3 h. The resulting fully degassed mixture is then left for ambient drying and solidification (lasting about 24 h). The procedure is displayed in Fig. 1 with examples of flexible manufactured samples shown in Fig. 2.

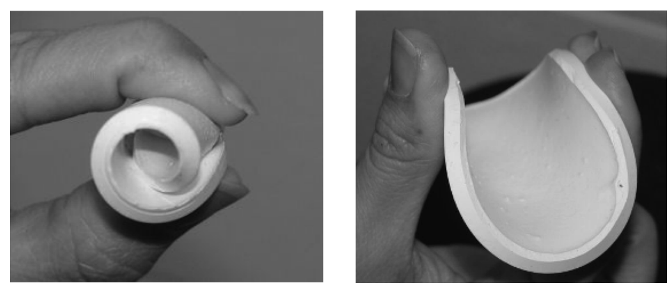
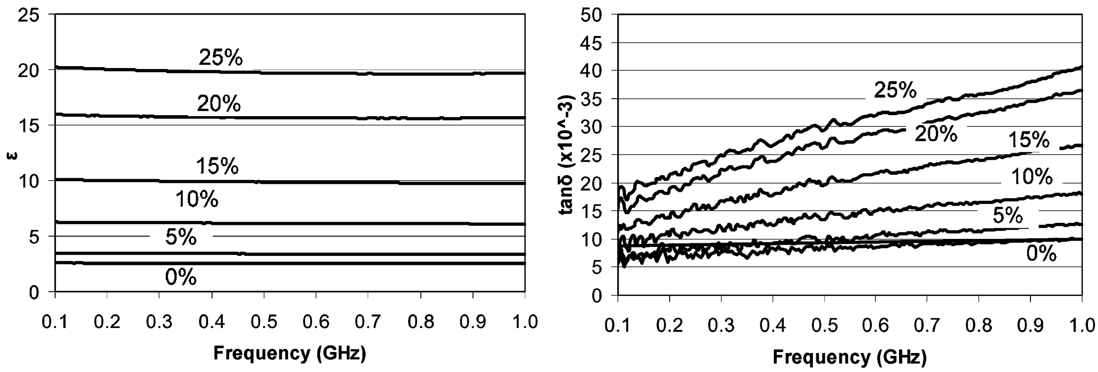


Fig. 2. Example fabricated polymer–ceramic substrates.

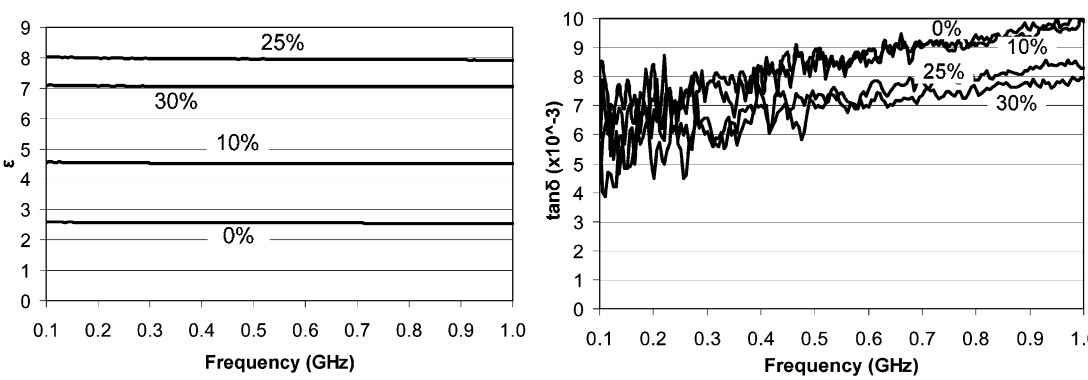
III. Material Properties of Polymer–Ceramic Substrates

Before using the bendable polymer–ceramic substrates, we proceeded to characterize their dielectric material properties, i.e., permittivity and loss tangents. We used an Agilent E4991A RF Impedance/Material Analyzer and 16453A calibration kit. The employed technique is actually based on capacitance measurements, and, as a reference load, we used a 0.78-mm-thick Teflon sample having a dielectric permittivity of $\varepsilon_r = 2.1$.



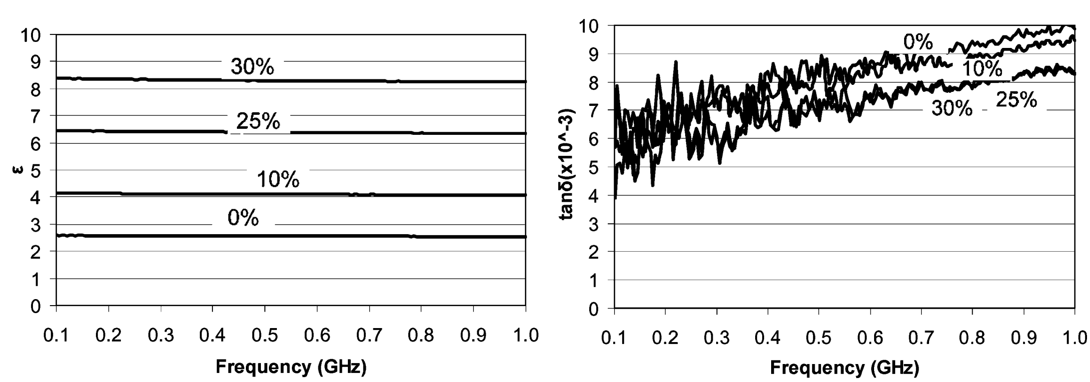
(a) (b)

Fig. 3. (a) Dielectric permittivity. (b) Loss tangent for the BT/PDMS samples at different volume ratios.



(a) (b)

Fig. 4. (a) Dielectric permittivity and (b) loss tangent for the MCT/PDMS samples at different volume ratios.



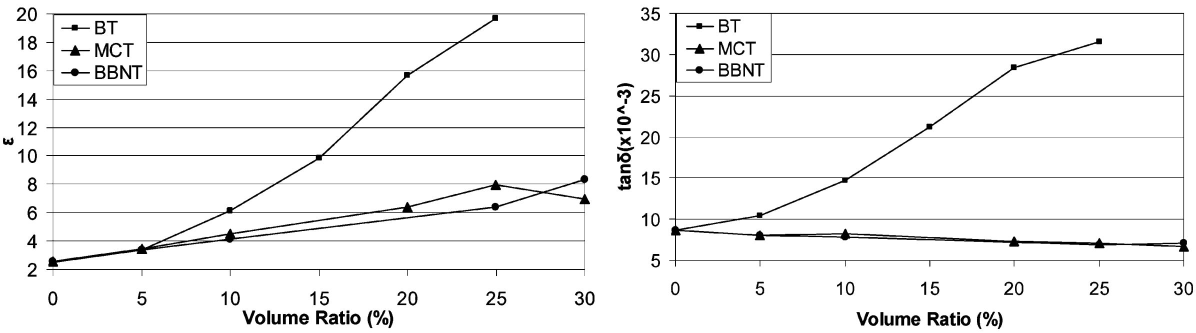
(a) (b)

Fig. 5. (a) Dielectric permittivity and (b) loss tangent for BBNT/PDMS samples at different volume ratios.

Different volume percentages of BT, MCT, and BBNT in a PDMS matrix as well as pure PDMS samples were fabricated and measured. The reported dielectric values for BBNT and MCT were $\varepsilon_r = 95$ and $\varepsilon_r = 140$, respectively. For the BT-PDMS composites, the maximum attainable volume percentage was 25%, whereas for MCT-PDMS and BBNT-PDMS composites the corresponding percentage was 30%. It should be noted that bubbles within the MCT and BBNT mixtures were encapsulated leading to lower dielectric values than it would be expected.

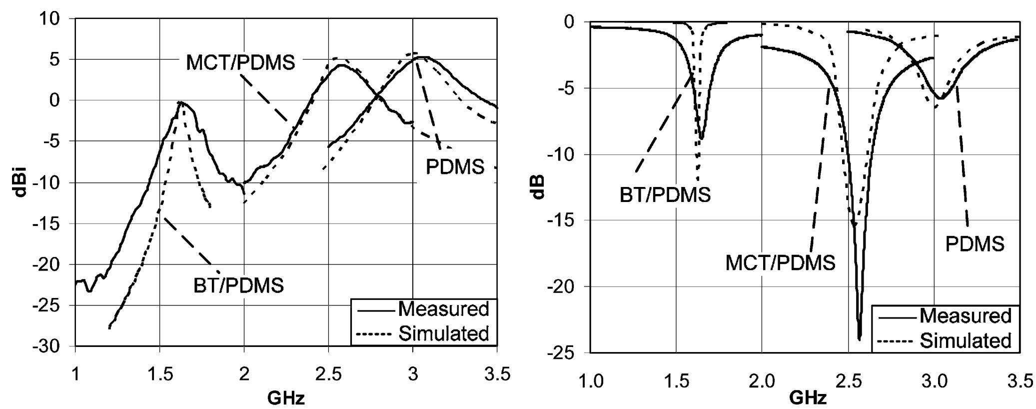
The measured permittivity and loss tangent versus frequency for the BT-PDMS composites are shown in Fig. 3. The permittivity remains almost constant in the measured 100-MHz–1-GHz window, except for a slight linear drop as the frequency increases. The maximum permittivity value was around $\varepsilon_r = 20$ for a 25% BT volume mixture, and similar results were reported in [14] and [15] for BT mixtures with polymers. However, the loss tangent increased as the volume ratio of BT also increased and was worse for higher frequencies. More specifically, the highest loss for a 10% BT mixture was $\tan\delta \approx 0.02$, whereas for the 25% mixture it was $\tan\delta \approx 0.04$ at 1 GHz.

Corresponding measurements for MCT/PDMS and BBNT/PDMS composites are shown in Figs. 4 and 5. The dielectric



(a) (b)

Fig. 6. (a) Dielectric permittivity and (b) loss tangent for the various volume ratios of the ceramics powders in the PDMS matrix.



(a) (b)

Fig. 7. (a) Gain and (b) return loss for a 24 mm × 24 mm patch antenna placed on a BT/PDMS substrate (20% volume ratio), a MCT/PDMS substrate (10% volume ratio) and a pure PDMS substrate.

permittivity is obviously lower as compared with the BT/PDMS mixtures discussed above with the 30% BBNT volume sample giving $\varepsilon_r = 8.3$. Similar values are observed for the MCT/PDMS mixtures as shown in Fig. 4(a). The nonlinear behavior of the measured ε_r for the MCT and PDMS samples is likely due to voids within the mixture. As far as the loss tangent is concerned, the MCT and BBNT mixtures show a consistent and fairly low loss tangent of $\tan\delta \leq 0.01$ in the 100-MHz–1-GHz range and for all the volume percentages up to 30%. The losses are primarily due to the PDMS content, and this is more apparent in Fig. 6, where we present the mean values of permittivity and loss tangent for all samples. As the volume ratio of the MCT or BBNT increases, the loss tangent decreases slightly. At the same time (see Fig. 6), we also observe that higher permittivity of the BT mixtures is obtained at the expense of higher losses.

IV. Microwave Applications Performance on Ceramic–Polymer Substrates

The above mentioned materials were used as substrates for two applications, namely, a patch antenna and a coupled line filter. The goal with the patch, apart from evaluating the polymer surface metallization process, was to evaluate the antenna gain and assess the loss-tangent impact.

A set of three patches were fabricated with metal epoxy used to print on the substrates. The rectangular patches having cross section of 24×24 mm^2 were printed on 20% BT volume, pure silicone, and 10% MCT volume mixtures 4-mm thick (see Fig. 7). The patches were fed by a 50 coaxial cable and simulations were carried out with Ansoft HFSS for comparison. As shown in Fig. 7(b), the measured and simulated return losses for the three samples are in agreement, thus verifying the previously found dielectric constants. A minor disagreement is only observed in the "depth" of the resonance, and this is likely due to the fact that feeding points between simulation and measurement may be slightly misplaced. The antenna gain measurements along with the corresponding simulated results for the three substrates are shown in Fig. 7(a). As expected, the higher BT/PDMS loss tangent leads to rather low gain of -0.5 dBi at boresight. In contrast, when the substrate is pure PDMS, the gain is recovered and is near $+5$ dBi. Moreover MCT/PDMS substrates give also high gain measurements close to 5 dBi. The difference (0.5 dB) between PDMS and MCT/PDMS substrates falls inside the measurement error.

To demonstrate the flexibility of the polymer substrates, we selected the MCT/PDMS substrate and printed on it a 36 cm × 36 cm patch. The substrate was 4-mm thick and was formed by mixing 10% MCT in volume with PDMS, resulting in an equivalent permittivity of $\varepsilon_r = 4.5$ and loss tangent $\tan\delta = 9 \times 10^{-3}$. Referring to Fig. 8, the patch was measured at three bending angles, namely 30°, 60°, and 90°, with the feed placed 7.5 mm from the center of the patch and along the dividing axis A of the patch as shown. The bending was done along the circumferential direction [18] [around the A axis in Fig. 8(a)] and

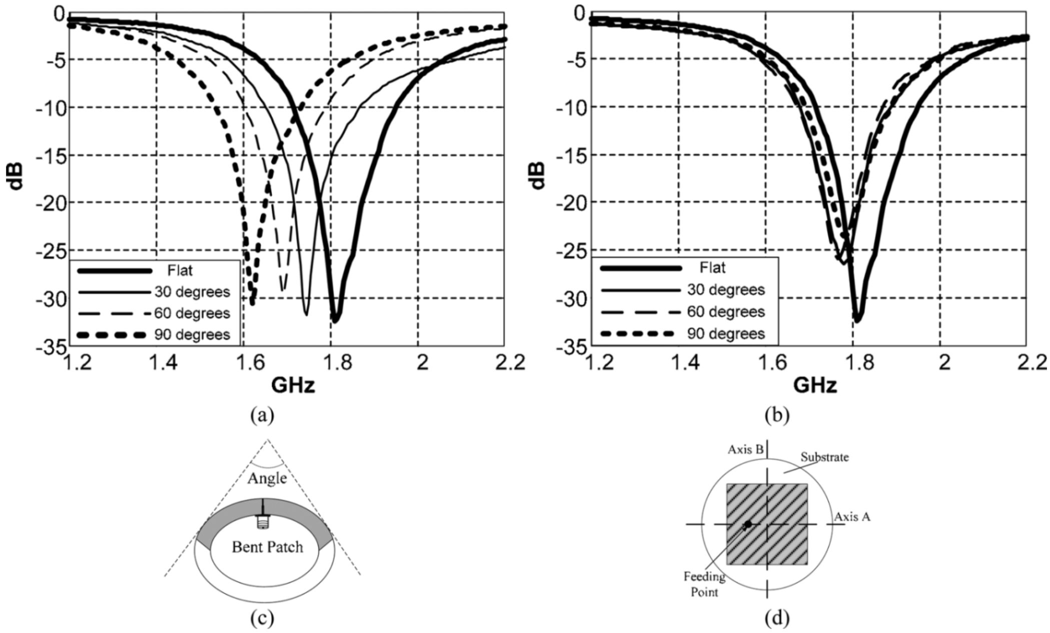


Fig. 8. Return loss patterns curves for a patch bent around circumferential (A axis) and axial (B axis) directions. The patch was 38 mm × 38 mm and was placed on 4 mm mixed with a 10% MCT volume substrate to yield a dielectric constant of 3.5. (a) S_{11} for circumferential bending (around the A axis), (b) S_{11} for axial bending (around the B axis), (c) geometrical display of the bending angle, and (d) patch projection showing the feed location and the axes of bending.

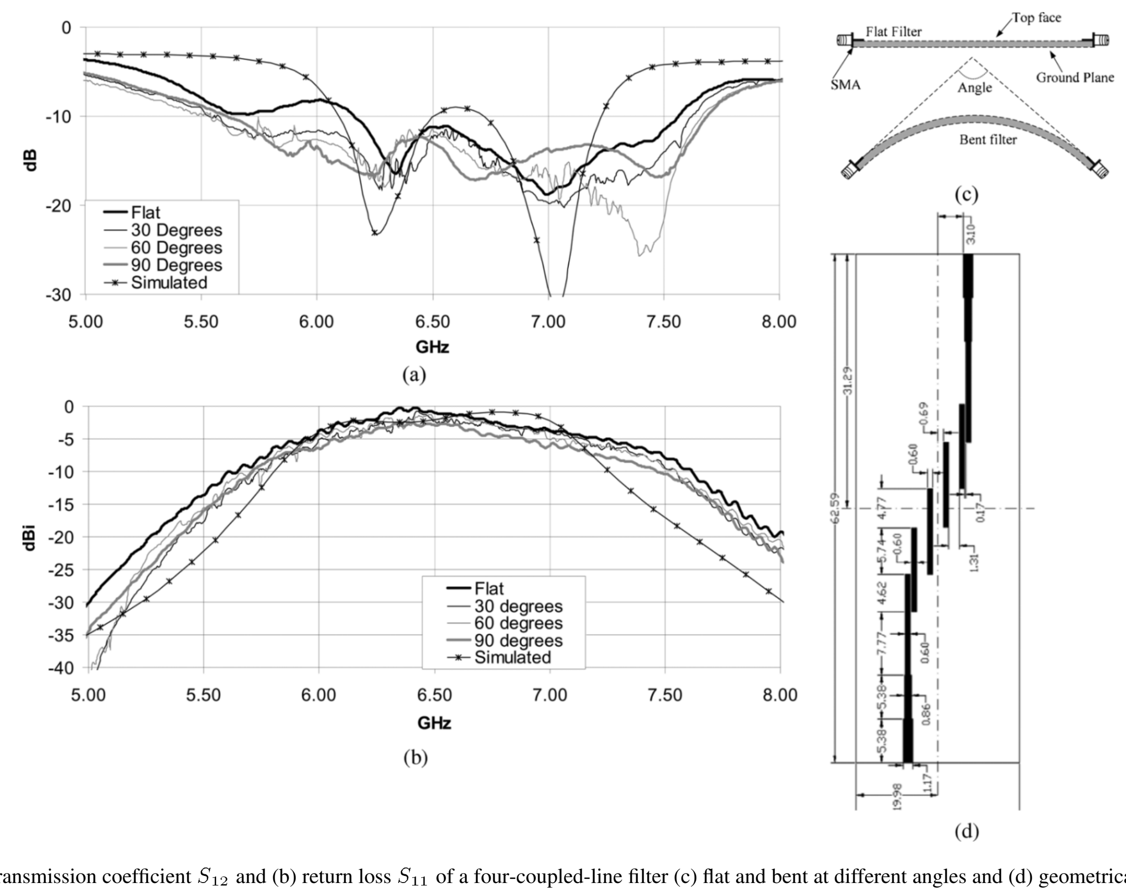


Fig. 9. (a) Transmission coefficient S_{12} and (b) return loss S_{11} of a four-coupled-line filter (c) flat and bent at different angles and (d) geometrical details of the filter (mm). The filter was placed on BBNT/PDMS substrate (15% volume ratio) 1.5-mm thick.

the axial direction [around the B axis in Fig. 8(b)] for a total of six configurations. It is clear from Fig. 8(a) that bending around the A axis (circumferential) shifts the patch resonance to lower frequencies. This is expected since the substrate is elongated due to its elastic properties. However, bending around the B axis has little effect [see Fig. 8(b)], as the resonance mode of the patch antenna is not affected this time. The reader is referred to [18] for a study on the radiation patterns and gain due to curvature.

As would be expected, the radiation pattern broadens when the bending increases.

Apart from the simple patches, we also designed, fabricated, and tested a microwave filter. This consisted of a four-coupled-line filter with its geometrical details given in Fig. 9(d). Two 50-Ω SMA probes were used for the input and output ports. They were matched to the filter by using a microstrip transmission line [see Fig. 9(d)]. The designed operating frequency of the filter was 6.6 GHz, and its bandwidth was 800 MHz. It was placed on a 1.5-mm-thick substrate of relative dielectric constant $\varepsilon_r = 5.8$ and a loss tangent of 0.9.

The manufacturing phase was completed in three steps. First, the substrate (a 15 vol% BBNT/PDMS sample) was prepared, and subsequently the filter (printed on an FR4 thin film—thickness less than 0.2 mm) was placed on the BBNT/PDMS substrate. After applying the feeding and the ground plane (copper tape), the structure was encapsulated into pure silicone (PDMS), which stabilized the printed film and allowed for "hard" handling of the filter. It was then measured in four different positions, flat and bent at three different angles 30°, 60°, and 90° [see Fig. 9(c)] as before for the patch. Shown in Fig. 9(a) is the measured and simulated transmission coefficients for the flat position. The results are seen to satisfy our goal giving values over -2 dB for nearly 700 MHz at the central frequency of 6.4 GHz. Nevertheless, there are some differences in the response, and this is attributed to the presence of air bubbles encapsulated between the filter layer and the substrate. This statement is supported by the return loss [see Fig. 9(b)] data showing good agreement between measurements and calculations (the substrate performance has been verified as well). Direct printing on the PMDS substrate is expected to eliminate this issue.

When the filter is bent, the general band performance does not change, but the transmission coefficient is decreased slightly. The transmission coefficient is affected more, of course, when the filter is bent at 90° presenting the highest value of -3 dB (probably due to radiation leakage). As far as the return loss is concerned [Fig. 9(b)], as the filter is bent, its return loss improves, which is probably due to the fact that less signal arrives at and reflects from the receiving side.

V. Discussion and Conclusion

We presented a novel approach for fabricating pliable substrates used for SoP technologies. A particular advantage of the ceramic–polymer mixtures relates to the capability of obtaining a wide range of dielectric constants while retaining pliability.

Our measurements showed that the BT/PDMS composites displayed high permittivity of up to $\varepsilon_r = 20$ but had losses $(\tan\delta < 0.04)$. In contrast, the MCT/PDMS and BBNT/PDMS mixtures exhibited low losses $(\tan\delta < 0.009)$ but were associated with lower dielectric permittivities $(\varepsilon_r < 8.5)$. To demonstrate the substrate performance, we constructed and measured patch antennas and a coupled line microwave filter on the PDMS substrates loaded with ceramic powders and showed satisfactory response in terms of predicted substrate permittivity and loss behavior. The filter and a patch antenna were measured in flat and in bent positions to demonstrate the substrate pliability/flexibility.

A further development of the proposed substrates would be the fabrication of mixtures having high dielectric permittivities $(\varepsilon_r > 20)$ with low loss characteristics $(\tan\delta < 0.01)$. To generate substrates with large volume ratios, we can slightly alter the fabrication method such us heating the produced mixtures during the fabrication process, since the original liquid gel would present more fluidity. At the same time, heating of the samples could lead to removal of unwanted air bubbles inside the ceramic/polymer composites. Use of powders with different grain size may also be considered to find an optimal composition for the desired substrate characteristics. Direct printing is another issue to be addressed for commercial repeatable stages.

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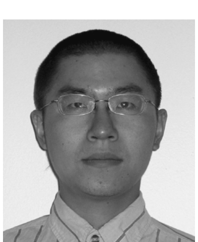

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