A New Model to Determine Effective Permittivity and Resonant Frequency of Patch Antenna Covered With Multiple Dielectric Layers

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ABSTRACT

This paper reports a model to determine effective permittivity ($\varepsilon_{\text{eff}}$) and resonant frequency ($f_r$) of microstrip patch antenna (MPA) covered with multiple dielectric layers. This model is augmented with a newly developed empirical expression to determine the $\varepsilon_{\text{eff}}$ of multi-layered superstrates over a substrate. The development of empirical formulation makes use of conformal mapping approach (CMA) and series–parallel combination of dielectric boundaries between the ground plane and patch of the MPA. In this work, the MPA is designed on substrate having dielectric constant of $\varepsilon_1$ whereas the superstrate layers have dielectric constants of $\varepsilon_2, \varepsilon_3 \ldots \varepsilon_n$. It is shown that the proposed technique is able to predict the $f_r$ of MPA with error of 1.8%, 3.5%, and 1.4% when it is covered with a single dielectric layer with superstrate height of 4.5mm for respective conditions of $\varepsilon_1 = \varepsilon_2$, $\varepsilon_1 > \varepsilon_2$ and $\varepsilon_1 < \varepsilon_2$ ($\varepsilon_1 = 3.66, \varepsilon_2 = 2.2/4.7$). Furthermore, the developed technique is analyzed for distinct combination of substrate and two superstrate layers for the cases $\varepsilon_1 = \varepsilon_2 > \varepsilon_3, \varepsilon_1 = \varepsilon_2 < \varepsilon_3, \varepsilon_1 < \varepsilon_2 > \varepsilon_3, \varepsilon_1 > \varepsilon_2 < \varepsilon_3$, and $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$. Subsequently, the viability of the proposed technique is demonstrated in practical scenarios for body centric communications by considering single (e.g., jeans cotton, pure cotton, rayon, polyester, felt fabric, terry wool, and leather) and multiple (e.g., wool over jeans cotton and polyester, felt fabric over pure cotton and rayon) layers of textiles over MPA. The measurement results on various dielectric superstrates and textiles show excellent agreement with the corresponding theoretical results and thereby validate the reported theory. Finally, a comparison with the seminal works clearly shows the promise of the reported technique in this paper.

INDEX TERMS

Body centric communication, conformal mapping (CM), conformal mapping approach (CMA), filling fraction, microstrip patch antenna (MPA), superstrate.

I. INTRODUCTION

MPAs possess low profile, light weight, and compact size and therefore find usefulness in myriad of communication applications such as hand held portable radio, mobile equipment, and IOT sensor [1]–[5]. Numerous applications often have antennas below dielectric layers for protection against environmental hazards and as a consequence the effective dielectric constant ($\varepsilon_{\text{eff}}$) of the MPAs covered with layers get altered significantly. Such scenarios shift the original resonant frequency ($f_r$) and hence lead to the out of band communication considering that MPAs exhibit narrow fractional bandwidth (2–3%) [6]–[7]. The body centric communication sensors are ready example of such a situation in which transmission happens through multiple layers of textiles and are adversely impacted due to multiple layers over MPAs [8]–[11]. This issue can be addressed by determining $\varepsilon_{\text{eff}}$ and shifts in the $f_r$ apriori. A literature survey reveals that a
number of techniques have been reported earlier and these include the complex methods namely variational, spectral, modified Wolff model, the full wave analysis, and the conformal mapping (CM) based techniques [12]–[22].

The comparison of the measured and theoretical \( f_r \) of the MPA covered with superstrates of permittivity \( 2.32, 2.6, \) and \( 3 \) for relatively thinner height exhibit errors of more than \( 4\% \), \( 4.5\% \), and \( 2.3\% \) in the variational method [12]. On the other hand, the spectral domain approach achieves very good accuracy in predicting \( f_r \) and the input impedance for similar configurations. However, this accuracy is for higher order mode, TM\(_{12}\) [13]. The modified Wolff model achieves accuracy of 0.5% w.r.t. measured results for relatively thicker heights. However, the report only exist for fewer superstrates and that too for substrates having identical dielectric constants [14]–[15]. The modified Wolff model suffers from serious limitations because in the first step it computes the real input impedance of MPA covered with multiple layers and then determines the modified \( f_r \). It leads to large shift in \( f_r \) due to propagation of error to successive stages. All these techniques, although, can determine \( f_r \) with reasonable accuracy but at the cost of high computational time and therefore find limited usefulness in integration with standard microwave simulators [19]–[21]. The CM based technique with simpler closed form expressions, although rely on approximation, can predict \( f_r \) of superstrate covered MPA with almost similar accuracy and is also compatible with software tools such as MATLAB [19]–[20]. For example, a square MPA covered with a dielectric, this technique can predict \( f_r \) with error of 0.22% which is better to variational method (2%) and modified Wolff model (0.89%) [19]. However, it has been observed that the CM based models exhibit higher error between the theoretical and measured \( f_r \) for superstrate of \( \varepsilon_r > 3 \). Therefore, the existing techniques are often constrained in emerging biomedical and e-health related applications as mentioned in the following points.

- A CM based technique uses quasi-static model to determine \( \varepsilon_{eff} \) for microstrip line covered with multi-layers of superstrate [21]. However, these are not good to compute \( \varepsilon_{eff} \) and \( f_r \) for MPA covered with multiple dielectric layers.

- The existing approach ignores the material present above the air gap for the determination of \( \varepsilon_{eff} \) and \( f_r \) [20]. This essentially means that the MPA is radiating into the infinitely thick spaced superstrate rather than the free space. However, such a scenario is highly unlikely in practice and hence the height of subsequent superstrate layers need to be taken into account in the determination of \( \varepsilon_{eff} \) and \( f_r \).

- The existing approaches have only analyzed the situation of superstrate covered MPA for substrate with permittivity smaller than 2.47 [12]–[20]. However, MPA designed on substrate with permittivity larger than 2.47 and covered with textiles are often used in dresses and clothes and thereby the techniques are not able to fulfill the current needs.

We had proposed a preliminary work based on CMA to address some of the above concerns [22]. This paper significantly expands the work and proposes following contributions to advance state-of-the-art [19]–[21].

- Development of a new empirical relation to determine \( \varepsilon_{eff} \) of MPA covered with superstrate layer. It makes use of CM and equivalent capacitance between the metallic plates partially covered by dielectric layers. It exhibits superior performance w.r.t. earlier reported CM based techniques.

- Development of a unique iterative model to determine \( \varepsilon_{eff} \) and \( f_r \) of MPA covered with either single or multiple layers of dielectric. It uses modified relation (in point \( a \)) in each iteration to determine \( \varepsilon_{eff} \) of the overall geometry. The earlier approaches (either numerical or CMA) evaluated \( \varepsilon_{eff} \) by substituting the total thickness of the superstrate in the expression and it is the fundamental drawback of these techniques. The proposed technique, on the other hand, allows fragmentation of multiple superstrate layers over the MPA to separately determine \( \varepsilon_{eff} \) and \( f_r \).

- The proposed method allows to consider the thickness of the dielectric over a spaced MPA. Furthermore, the proposed method also allows to restore the original \( f_r \) of MPA covered with dielectric layers by modifying its physical parameters.

The validation of the proposed method is carried out by designing MPAs operating at 2.38 GHz on substrate (\( \varepsilon_f \)) RO4350B and FR4. It is then investigated with covering of several superstrate layers such as RO4350, RO5880, FR4, cotton, wool, rayon etc. First, the model and the formulation is analyzed by combining two superstrate layers namely RO5880 (\( \varepsilon_3 \)) over RO4350B (\( \varepsilon_2 \)). During investigation, an intermediate permittivity (\( \varepsilon_{eff} \)) of the first superstrate and substrate is computed and then \( \varepsilon_1 = \varepsilon_{eff} \) is taken to determine the overall \( \varepsilon_{eff} \) of the whole structure. Finally, extensive analysis for the MPA covered with multiple layers of textiles such as felt fabric over pure cotton and rayon, terry wool over jean cotton etc. that mimic typical scenarios of sensors in body centric communication is also carried out. The theoretical analysis is then augmented with CST simulation results to expedite the verification of the proposed technique. The use of commercially available antenna simulator allows study of number of cases (with multiple substrate/superstrate thicknesses) without any prototyping of all those test cases. The proposed technique is then benchmarked against the well-known CM based techniques [19]–[21].

It is imperative to mention that the proposed model, even though iterative, allows determination of resonant frequency in very short time in comparison to standard simulation software tool such as CST which relies on mesh settings for higher accuracy. For example, an antenna designed on RO4350B, with height of 1.524mm and permittivity of 3.66,
and covered with identical layer of dielectric takes 5 and 4.3 minutes for mesh cells of around 280,000 on i5 and i7 processors respectively in CST. For this case, the proposed model takes around 1.2s with a nominal error of 0.2% w.r.t. simulation in MATLAB (described in section IV). The mesh cells and simulation time will drastically increase for complex designs like antenna array, conformed antenna, and MPA covered with multiple or thick dielectric layers [23]. Furthermore, to restore the original $f_s$ of the dielectric covered MPA, backtracking approach to modify the dimension of the MPA has to be adopted which further increases the simulation time in any standard simulator. Interestingly for the proposed approach, substitution of the determined effective permittivity in the standard expression results in modified dimensions. This effectively reduces the simulation time and leads to the expedited design process.

Section II presents the formulation of the modified closed form expressions to determine $\varepsilon_{\text{eff}}$ based on series–parallel combination of capacitances between the metallic layers of the patch and the ground plane. Section III explains the iterative model and a MATLAB compatible algorithm. Section IV includes the analysis of the developed technique for single layered superstrate structures along with the textiles whereas section V provides the development of model for two superstrate structures over the MPA. The section VI compares the theoretically obtained results with the measured results while section VII concludes the paper.

II. FORMULATION OF EFFECTIVE PERMITTIVITY FOR SINGLE SUPERSTRATE LAYER OVER MPA

An MPA designed on substrate with permittivity $\varepsilon_s$, region shaded in brown, and height $h$ having length and width of $W$ and $L$ respectively is shown in Fig. 1. It is covered by a superstrate layer of permittivity $\varepsilon_q$ and height $h_2 - h$, the region shaded in red. For $W/h > 1$, CM is applied at the two interfaces namely substrate ($\varepsilon_s$)/superstrate ($\varepsilon_q$) and superstrate ($\varepsilon_q$)/air ($\varepsilon_0$) using Wheeler’s transformation [17]–[18]. It means that the angle of refraction at the interfaces ($x - y$) must be retained while conforming the dielectric boundaries to complex flux–potential plane shown in Figs. 2(a)–(b). The terms $q_0$, $q_1$, and $q_2$ are the effective filling fractions of air, substrate, and superstrate boundaries defined by ratio of area occupied by a given dielectric ($S_{\varepsilon_1}$, $S_{\varepsilon_2}$, $S_{\varepsilon_0}$) to overall area ($S$). For example, $q_1$ is given by ratio of area for the substrate, $S_{\varepsilon_1}$ and the whole area, $S$, in the $W$-plane [18]. The overall filling fraction, $q$, in terms of $q_0$, $q_1$, and $q_2$ is expressed in (1).

$$q = q_1 + q_2 + q_0 = \frac{S_{\varepsilon_1}}{S} + \frac{S_{\varepsilon_2}}{S} + \frac{S_{\varepsilon_0}}{S} = \frac{S_{\varepsilon_1} + S_{\varepsilon_2} + S_{\varepsilon_0}}{S}$$  \hspace{1cm} (2)

This work uses the expressions for filling fractions $q_0$, and $q_1$ for an MPA with width, $W$, given in [18]. However, expression of $q_2$ has some inconsistency for $h_2 = h$ and hence makes use of expression (3) to include this case [20]. Moreover, the effective width of the patch that takes into account the fringing at the edges, $W_{\text{eff}}$, and the extent of superstrate layer in imaginary axis of $W$-plane, $V_s$, depicted in Figs. 2(b)–(c) are expressed in (4) – (5) [18].

$$q_{2\text{new}} = 1 - q_1 - q_0 - \frac{h}{2W_{\text{eff}}} \ln \left( \frac{\pi}{2} - \frac{h}{2W_{\text{eff}}} \right)$$  \hspace{1cm} (3)

$$W_{\text{eff}} = W + 2h \left( 17.08 \frac{W}{2h} + 0.92 \right) \hspace{1cm} (4)$$

$$V_s = \frac{2h}{\pi} \tan^{-1} \left( \frac{\pi}{2} \frac{W}{h} - 2 \frac{h}{h_2 - 1} \right) \hspace{1cm} (5)$$

Furthermore, the respective capacitance per unit area of the substrate regions, $S_{\varepsilon_1}$, $S_{\varepsilon_0}$, and $S_{\varepsilon_2}$, can be expressed as $C_1 = (\varepsilon_1 q_1)h$, $C_0 = (\varepsilon_0 q_0)h_1$, and $C_2 = (\varepsilon_2 q_{2\text{new}})V_s/\varepsilon_\varepsilon$. Here, $h_1 = h - V_s$. The series equivalent capacitance, $C_{\text{eqs}}$, between $C_0$ and $C_2$ is expressed in (6) and hence the equivalent capacitance, $C_{\text{eff}}$, of the arrangement in Fig. 2(c) consists of parallel combination of $C_1$ and $C_{\text{eqs}}$ is expressed in (7). The expressions (6)–(7) can be simplified using $C_1$ to get (8). This effective capacitance in terms of effective permittivity, $\varepsilon_{\text{eff}}$, the overall filling fraction, $q$, and the total height of the arrangement, $h_2$, is then expressed by (9). Finally, (1), (8)–(9) can be used to obtain expression for $\varepsilon_{\text{eff}}$ in (10) [22]. Further simplification $\varepsilon_{\text{eff}}$ in (11) is achieved by making use of $C_{\text{eqs}}$ given in (12).

$$C_{\text{eqs}} = \frac{\varepsilon_2 q_{2\text{new}} q_0}{\varepsilon_2 q_{2\text{new}} h_1 + \varepsilon_0 q_0 V_s}$$  \hspace{1cm} (6)

![FIGURE 1. MPA with dimensions $W$ and $L$ covered with a single superstrate layer.](image-url)

![FIGURE 2. (a) Refraction of EM wave travelling from a dielectric medium to air (Snell’s law) [$q_1$ and $q_2$ are incident and refracted angles of EM wave] (b) Conformed dielectric boundaries in flux-potential plane ($W$-plane) (Shaded portions indicates: red–superstrate, brown–substrate, and white–air), (c) Approximation of dielectric boundaries $q_0$ and $q_2$ with associated permittivities.](image-url)
\[
C_{\text{eff}} = C_{\text{eqs}} + C_1 \tag{7}
\]

\[
C_{\text{eff}} = \frac{\epsilon_2 q_2 \text{new} \epsilon_0 q_0}{h_1 + \epsilon_0 q_0 V_e} + \frac{\epsilon_1 q_1}{h} \tag{8}
\]

\[
\epsilon_{\text{eff}} = \frac{\epsilon_1 q_1 h_2}{h} + \frac{\epsilon_2 q_2 \text{new} \epsilon_0 q_0 h_2}{2} \tag{9}
\]

\[
\epsilon_{\text{eqs}} = \frac{\epsilon_2 q_2 \text{new} \epsilon_0 q_0 h_2^{\text{new}}}{\epsilon_2 q_2 \text{new} h_1 + \epsilon_0 q_0 V_e} \tag{10}
\]

It can be inferred from (11) and (12) that the known values of \(\epsilon_0, \epsilon_1, \epsilon_2, h, h_2\) and the computed values of \(W_{\text{eq}}, V_e, q_0, q_1, q_2\text{new}\) can enable the determination of \(\epsilon_{\text{eff}}\) of the combination of layers depicted in Fig. 1. Apparently, this proposed formulation takes into account the height of the single superstrate layers and therefore aid in the accurate determination of \(\epsilon_{\text{eff}}\) unlike the technique reported in [20]. Furthermore, the proposed formulation and the model proposed here to determine \(\epsilon_{\text{eff}}\), although based on CM, is distinct from the seminal works [19–20].

III. PROPOSED MODEL FOR SINGLE SUPERSTRATE LAYER

The flow chart depicted in Fig. 3 includes all the steps involved in the calculation of \(\epsilon_{\text{eff}}\) and \(f_r\) of the MPA shown in Fig. 1. It is important to mention that the proposed model does not take into account the theoretically obtained length of the MPA rather it considers the optimized simulated values unlike the seminal works [19–20]. This is because theoretically obtained length and width of the MPA for a given \(f_r\) assumes ground plane and substrate is of infinite extent. However, practical MPAs always have finite dimensions of ground plane and substrate and hence the antenna designed with these values in simulation software (CST) often show shift from the actual \(f_r\). Apparently, the design of MPA on a given substrate is the first step followed by covering of dielectric layer, all the physical parameters of MPA are independent of cover characteristics. Following steps which explain the flow chart is analyzed using MATLAB.

Step 1: Choose the substrate, superstrate, and antenna’s parameters such as height, permittivity, length, and width. Here, actual superstrate’s height is \(\Delta h = h_2 - h\) from Fig. 1. The total height of the substrate and the superstrate is taken as \(h_2^{\prime}\) given by \(h_2^{\prime} = h + n\). As a consequence, \(h_2\) in (5), (9)-(12) is replaced by \(h_2^{\prime}\). The superstrate layer in this model is divided into ‘N’ smaller blocks of thickness ‘\n’ each. Selection of \(n\) is explained using an example whereas selection of \(N\) is elaborated in step 3. Say, an MPA designed on substrate RO4350B of permittivity and height of 3.66 and 1.524 mm is covered by a dielectric identical to the substrate. This makes \(h_2^{\prime} = 1.524 + n\) mm. For \(n = 0.1\) mm, \(\epsilon_{\text{eff}} = 3.679\) using (3)-(12). For any smaller \(n\), say 0.09 or 0.08 mm, the value of \(\epsilon_{\text{eff}}\) is smaller than 3.66. Thus, \(n\) assumes the limiting value for which \(\epsilon_{\text{eff}}\) is just greater than \(\epsilon_1\). It is obvious that for larger \(n\), say 0.11 mm or any other value, the \(\epsilon_{\text{eff}}\) will be greater than \(\epsilon_1\) but due to iterative nature of the model the value becomes impractically larger for thicker superstrates. As a simple rule, \(n\) starts from 0.01 and ends at the value for which \(\epsilon_{\text{eff}} > \epsilon_1\) with step size of 0.01.

Step 2: Use the parameters from step 1 to determine the values of \(W_{\text{eq}}\) and \(V_e\) using (4)–(5).

Step 3: Compute the filling fractions \(q_0, q_1, q_2\text{new}\). Filling fraction of air, substrate, and superstrate respectively \(q_0\) and \(q_2\text{new}\) are used in (6) to find the maximum iterations (no. of blocks) required to calculate \(\epsilon_{\text{eff}}\). As an example, \(\Delta h = 1.524\) mm and \(n = 0.1\) gives \(N = 15\) and this implies that the loop in Fig. 3 will run 15 times and modified \(\Delta h\) for which the model calculates \(\epsilon_{\text{eff}}\) is 0.1 + 15 = 1.5 mm instead of 1.524 mm. Similarly, \(N = 16\) for \(\Delta h = 1.575\) mm and \(n = 0.1\) and therefore \(\epsilon_{\text{eff}}\) is determined for modified \(\Delta h = 1.6\) mm. Apparently, the model may underestimate or overestimate \(\epsilon_{\text{eff}}\) based on \(\Delta h\). However, it will be shown later that this difference is very less and does not have a significant impact.

Step 4: Initialize counter, \(i\). The permittivity of the substrate, \(\epsilon_1\), gets updated in each loop. As a starting point \(\epsilon_1 = \epsilon_1\). Just for clarity, \(\epsilon_i\) for \(i = 1, 2 \ldots N\) should not be confused with permittivities of substrate and superstrates.

Step 5: Use (10)-(12) to compute \(\epsilon_{\text{eqs}}\) and \(\epsilon_{\text{eff}}\). Reassign \(\epsilon_1\) to newly computed \(\epsilon_{\text{eff}}\). In this model, open end extension of the patch is modelled in the form of fringing length \(\Delta L\) and is taken into account appropriately [24].
TABLE 1. Physical and electrical parameters of the antenna, and feed line designed on RO4350B.

| Antenna para. | Value | Antenna para. | Value |
|---------------|-------|---------------|-------|
| Length of l/4 line (mm) | 17 | Quarter-wave transformer impedance (3/4) | 119 Ω |
| Width of primary feed (50 Ω) line (mm) | 3.6 | Effective permittivity | 3.34 |

Step 6: Determine $f_r$ of the MPA using (13) [7].

$$f_r = \frac{c}{2(L + \Delta L) \sqrt{\varepsilon_{eff}}}$$ (13)

Step 7: Use (14) to determine the percentage variation between the simulated and theoretically computed $f_r$.

$$\%\text{var.} = \left| \frac{f_r(\text{Sim.}) - f_r(\text{Th.})}{f_r(\text{Sim.})} \right|$$ (14)

Step 8: It is a conditional check. If $i \leq N$ then the counter is incremented by $i = i+1$ else the loop breaks which indicates completion of all steps.

Following aspects are kept in perspectives in the aforementioned steps:

- For the proposed model, $h_2'$ remains constant as it depends on two fixed quantities $h$ and $n$.
- The frequency dispersion generally decreases for wider conductor (here patch), hence it has not been considered in this model.

IV. ANALYSIS FOR SINGLE SUPERSTRATE LAYER

Extensive simulation using CST has been carried out for MPA covered with single dielectric layer. For this purpose, an MPA is designed on RO4350B with permittivity of 3.66 and thicknesses of 1.524mm. The physical and electrical parameters of the MPA determined by standard expressions in [7] are given in Table 1. A quarter wave transformer matching is used to feed the patch of the MPA with a primary feed line of 50Ω. The electrical and physical parameters of the line are also given in Table 1.

A. SINGLE LAYER OF DIELECTRIC OVER MPA

The designed MPA is covered by superstrate layers, RO4350B, RO5880 ($\varepsilon_2 = 2.2$) and FR4 ($\varepsilon_2 = 4.7$) in such a way that all the conditions $\varepsilon_1 = \varepsilon_2$ (case 1), $\varepsilon_1 > \varepsilon_2$ (case 2), and $\varepsilon_1 < \varepsilon_2$ (case 3) are met. It is important to mention that the formulations derived in this paper are applicable for materials with higher permittivity as well but in this paper superstrate with maximum permittivity of 4.7 is considered to facilitate the in-house fabrication.

The theoretical and simulated results for all the three cases up to the height of 4.5mm are given in Tables 2–4.

These tables also provide results obtained from two seminal CM based techniques [19]–[20]. The reason for comparing the proposed work with only [19]–[20] is due to the fact that both these works are considered seminal. Moreover, other reports also make use of the scenarios in these papers and employ the reported expressions in them. The results in Tables 2–4 enable following inferences:

- The proposed model achieves superior performance in terms of relative error in comparison to [19]–[20]. However, for case 2, the % variation is higher for $\Delta h = 4.5$mm w.r.t. [19]. Apparently, for a superstrate of $\varepsilon_2 \leq 2.2$ and smaller heights (1mm – 3mm) the proposed model and the formulation determines $\varepsilon_{eff}$ and $f_r$ with better accuracy, but it decreases for larger height.
- First and second rows of Tables 2 and 4 convey that the % variation for the reported technique goes slightly out of pattern. A careful observation of (14) and the values in Tables 2 and 4 agree to the fact that it increases from more negative value to more positive.
- The earlier CM based models [19]–[20] determine $\varepsilon_{eff}$ through closed form expressions whereas the proposed model is iterative. But it is still fair to compare the obtained results because the proposed model uses modified closed form expressions at each iteration. The only difference from the earlier techniques is that the initial value of substrate permittivity in the proposed model gets updated after each iteration.

It is important to mention here that though frequency dispersion has not been taken into account for the proposed approach and [19]–[20], still the proposed approach outperforms these two.

B. SINGLE LAYER OF TEXTILE OVER MPA

The antenna in wearable sensor has to send data through multiple layers of textile such as cotton, rayon, polyester, wool. Often there may be combination of textiles such as woolen jacket over cotton, felt jacket over polyester and many more. Therefore, textile layers in this analysis is divided in two sets. The first set of textile are immediately next to MPA and comprises of cotton, rayon, and polyester whereas the second set of layer next to first layer is often wool and felt fabric (hoodie). This section limits the analysis for MPA covered with some common textiles both for the proposed model and other CM based models [19]–[20]. The thickness of the textile layers has been taken from earlier reports [25]–[26]. For thinner superstrates (0.2–0.3 mm), it is apparent that the variation in $f_r$ using the proposed technique is much smaller when compared to well-known CM based techniques [19]–[20]. However, for the thicker superstrates (1–1.5 mm), the variation in $f_r$ increases when compared to [19]. These results are consistent with the outcome in Table 3 and therefore it can be inferred that the variation in $f_r$ is very low for superstrates with $\varepsilon_2 \leq 2.2$ and smaller height when compared to [19]–[20]. However, the variations in $f_r$ for superstrates
TABLE 2. Comparison of simulated and theoretically obtained resonant frequencies of the MPA in this work with [19] and [20] for superstrate of permittivity $\varepsilon_2 = 3.66$ (Case 1: $\varepsilon_1 = \varepsilon_2$) $[\Delta h = h_2-h_1, L = 31.5$ mm, $W = 41.3$ mm, $\varepsilon_1 = 3.66, h_1 = 1.524$ mm at 2.38].

| $\Delta h$ (mm) | $\varepsilon_{\text{eff}}$ [19] | $\varepsilon_{\text{eff}}$ [20] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [19] | Th. Freq. (GHz) [20] | Th. Freq. (GHz) [Prop.] | %var. [19] | %var. [20] | %var. [Prop.] |
|-----------------|-----------------|-----------------|-------------------|------------------|------------------|-------------------|----------|----------|----------|
| 1.0             | 3.56033         | 3.5010          | 2.317             | 2.401            | 2.434            | 2.438             | 3.61     | 5.05     | 0.91     |
| 1.5             | 3.62811         | 3.5148          | 3.9189            | 2.305            | 2.392            | 2.429             | 3.80     | 5.40     | 0.30     |
| 3.0             | 3.69321         | 3.5430          | 4.1277            | 2.284            | 2.372            | 2.421             | 3.86     | 5.95     | 0.70     |
| 4.5             | 3.7485          | 3.5616          | 4.3006            | 2.270            | 2.358            | 2.414             | 3.88     | 6.34     | 1.76     |

TABLE 3. (Case 2: $\varepsilon_1 > \varepsilon_2$, where $\varepsilon_1 = 3.66$, and $\varepsilon_2 = 2.2$) (Note: Th. and Prop. signifies theoretical value and proposed method).

| $\Delta h$ (mm) | $\varepsilon_{\text{eff}}$ [19] | $\varepsilon_{\text{eff}}$ [20] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [19] | Th. Freq. (GHz) [20] | Th. Freq. (GHz) [Prop.] | %var. [19] | %var. [20] | %var. [Prop.] |
|-----------------|-----------------|-----------------|-------------------|------------------|------------------|-------------------|----------|----------|----------|
| 1.0             | 3.5966          | 3.4742          | 2.347             | 2.403            | 2.443            | 2.336             | 4.20     | 4.10     | 0.45     |
| 1.5             | 3.6190          | 3.4805          | 3.9147            | 2.341            | 2.395            | 2.441             | 3.20     | 4.27     | 1.20     |
| 3.0             | 3.6772          | 3.4956          | 3.9887            | 2.350            | 2.377            | 2.437             | 2.86     | 4.62     | 1.58     |
| 4.5             | 3.7257          | 3.5023          | 4.1711            | 2.316            | 2.362            | 2.434             | 1.82     | 4.90     | 3.15     |

TABLE 4. (Case 3: $\varepsilon_1 < \varepsilon_2$, where $\varepsilon_1 = 3.66$, and $\varepsilon_2 = 4.7$).

| $\Delta h$ (mm) | $\varepsilon_{\text{eff}}$ [19] | $\varepsilon_{\text{eff}}$ [20] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [19] | Th. Freq. (GHz) [20] | Th. Freq. (GHz) [Prop.] | %var. [19] | %var. [20] | %var. [Prop.] |
|-----------------|-----------------|-----------------|-------------------|------------------|------------------|-------------------|----------|----------|----------|
| 1.0             | 3.6058          | 3.5192          | 2.305             | 2.400            | 2.428            | 2.328             | 4.12     | 5.34     | 1.00     |
| 1.5             | 3.6315          | 3.5381          | 3.9196            | 2.287            | 2.391            | 2.422             | 3.67     | 5.89     | 0.77     |
| 3.0             | 3.6996          | 3.5766          | 4.1307            | 2.260            | 2.370            | 2.409             | 4.87     | 6.60     | 0.44     |
| 4.5             | 3.7581          | 3.6019          | 4.3017            | 2.242            | 2.352            | 2.401             | 4.92     | 7.10     | 1.43     |

V. MODEL FOR TWO SUPERSTRATE LAYERS

The Fig. 4(a) depicts a scenario of MPA covered by two dielectric layers namely superstrate#1 and 2. The height and permittivity of the additional dielectric layer is $\Delta h_1 = h_3-h_2$ and $\varepsilon_3$. The technique presented here is an extension of the concept where a MPA is covered with single dielectric layer.

A. TWO SUPERSTRATE LAYERS OVER MPA

The determination of $\varepsilon_{\text{eff}}$ of the structure in Fig. 4(a) consists of two steps. First, fragmentation of two superstrate layers over the MPA as depicted in Fig. 4(b). Then $\varepsilon_{\text{eff}}(h_2)$ is computed using the proposed model in section III. Then, the fragmented dielectric layer is restored over the MPA as shown in Fig. 5(a) and the $\varepsilon_{\text{eff}}(h_3)$ is computed. The key point in the second step is that the term $\varepsilon_1$ is replaced by $\varepsilon_{\text{eff}}(h_2)$, and this scenario is depicted in Fig. 5(b), before using the single layer model formulations. Figs. 4 and 5(a) convey that $\varepsilon_{\text{eff}}$ for the first superstrate becomes permittivity of the substrate in the second step.

Following additional steps in conjunction with flowchart in Fig. 3 are required to determine $\varepsilon_{\text{eff}}(h_3)$.

• Choose $\Delta h_1$ and $\varepsilon_3$ of the second superstrate layer.

First, determine ‘$n$’ which might be different from the first superstrate. However, it has been identified that if the values of permittivities of the first and second
The results are elaborated below.

The value of \( \varepsilon \) of the antenna and feed line given in Table 6. Tables 7-11 lists case 5, the MPA is designed on FR4 using the new parameters cases 1-4 are designed using the parameters in Table 1. For the layer varies from RO5880 to FR4. Therefore, the MPA for the cases 1-4, the substrate is RO4350B while the superstrate all the possible combination of substrate and superstrate. For studies such as MPA covered with two superstrate layers. Number of case MPA considered with two superstrate layers. Number of case studies such as \( \varepsilon_1 = \varepsilon_2 > \varepsilon_3 \), \( \varepsilon_1 = \varepsilon_2 < \varepsilon_3 \), \( \varepsilon_1 < \varepsilon_2 > \varepsilon_3 \), \( \varepsilon_1 > \varepsilon_2 < \varepsilon_3 \), and \( \varepsilon_1 > \varepsilon_2 > \varepsilon_3 \) are studied as they include all the possible combination of substrate and superstrate. For the cases 1-4, the substrate is RO4350B while the superstrate layer varies from RO5880 to FR4. Therefore, the MPA for the cases 1-4 are designed using the parameters in Table 1. For the case 5, the MPA is designed on FR4 using the new parameters of the antenna and feed line given in Table 6. Tables 7-11 lists the value of \( \varepsilon_{\text{eff}} \) and \( f_r \) of all the cases mentioned above and the results are elaborated below.

- The tables list \( \varepsilon_{\text{eff}} \) and \( f_r \) for three different heights of superstrate#1 and 2. For example, MPA covered with second superstrate of \( \Delta h_1 = 1 \) mm, the \( \varepsilon_{\text{eff}} \) and \( f_r \) are calculated for \( \Delta h \) of 1, 1.5, and 2.5 mm. Similarly for \( \Delta h_1 = 1.5 \) mm and \( \Delta h_1 = 2.5 \) mm.
- Apparently, the variation in \( f_r \) obtained from the proposed model is much lower when compared to the model in [21]. Finally it can be inferred that the variation in \( f_r \) for the proposed model is lower than 2% for overall superstrate thickness of 5 mm over the MPA.
- The variation gradually increases for the proposed model for a given \( \Delta h \) and \( \Delta h_1 \) and it appears, Tables 9 and 11, that the variation has no pattern. But, in reality the simulated and theoretical \( f_r \) varies from more negative value to more positive and hence the pattern.

### TABLE 5. Comparison of simulated and theoretically obtained resonant frequencies of the MPA covered by different textile layers as superstrate in this work with [19] and [20].

| Material       | \( \varepsilon_1 \) | \( \Delta h \) (mm) | \( \varepsilon_{\text{eff}} \) [19] | \( \varepsilon_{\text{eff}} \) [20] | \( \varepsilon_{\text{eff}} \) [Prop.] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [19] | Th. Freq. (GHz) [20] | Th. Freq. (GHz) [Prop.] | %var. [19] | %var. [20] | %var. [Prop.] |
|-----------------|---------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------|-------------------|-------------------|-------------------|------------|------------|------------|
| Polyester       | 1.40                | 0.3                 | 3.557                         | 3.455                         | 3.714                         | 2.572                 | 2.4081            | 2.4424           | 2.3655            | 1.52      | 3.00       | 0.27       |
| Jeans           | 1.60                | 0.3                 | 3.558                         | 3.456                         | 3.714                         | 2.573                 | 2.4077            | 2.4420           | 2.3620            | 1.50      | 2.91       | 0.46       |
| Pure cotton     | 1.70                | 0.2                 | 3.554                         | 3.455                         | 3.697                         | 2.374                 | 2.4092            | 2.4420           | 2.3670            | 1.48      | 2.86       | 0.29       |
| Rayon           | 3.20                | 0.2                 | 3.558                         | 3.465                         | 3.698                         | 2.365                 | 2.4080            | 2.4380           | 2.3635            | 1.82      | 3.09       | 0.06       |
| Felt fabric     | 1.22                | 1.5                 | 3.604                         | 3.455                         | 3.910                         | 2.363                 | 2.3976            | 2.4422           | 2.3007            | 1.46      | 3.35       | 2.64       |
| Terry wool      | 1.30                | 1.5                 | 3.606                         | 3.457                         | 3.907                         | 2.358                 | 2.3922            | 2.4415           | 2.3005            | 1.45      | 3.54       | 2.44       |
| Leather         | 1.30                | 1.5                 | 3.613                         | 3.470                         | 3.913                         | 2.353                 | 2.3902            | 2.4382           | 2.3000            | 1.58      | 3.62       | 2.25       |

### TABLE 6. Physical and electrical parameters of the antenna and feed line designed on FR4.

| Antenna para. | Value | Antenna para. | Value | Antenna para. | Value |
|---------------|-------|---------------|-------|---------------|-------|
| \( L \) (mm)  | 27.7  | Patch Impedance | 281 \( \Omega \) | Length of \( \lambda/4 \) line (mm) | 15.8  |
| \( W \) (mm)  | 38.5  | Quarter-wave transformer (\( \lambda/4 \) impedance | 118 \( \Omega \) | Width of primary feed (50 \( \Omega \) line (mm) | 2.8   |
| Effective permittivity | 3.946 | Width of \( \lambda/4 \) line (mm) | 0.37  | Length of 50\( \Omega \) line (mm) | 5.6   |

### B. TWO TEXTILE LAYERS OVER MPA

The designed MPA on RO4350B is taken as a source of EM wave. Subsequently, it is covered by combinations of textile layers mentioned in Table 12 to analyze the proposed technique. Layer 1 consist of textiles which are next to MPA such as pure cotton, jeans cotton, rayon and polyester. Layer 2 consist of textile which are worn over the layer 1 in real life such as woolen jackets and hoodies made of felt. The approach adopted here makes use of the technique proposed for single superstrate in this paper and an earlier method [19] to determine \( f_r \) and \( \varepsilon_{\text{eff}} \) for such arrangements. It is done to overcome the specific limitations of the proposed technique whenever the % variation is higher when compared to the earlier approach [19] for covers like wool and felt (layer 2) as can be seen in Table 5. The idea here is to first determine \( \varepsilon_{\text{eff}} (h_2) \) that constitutes layer 1 over MPA using the proposed technique. The arrangement over the MPA then reduces to one superstrate layer after the determination of \( \varepsilon_{\text{eff}} (h_2) \) and depicts the scenario shown in Fig. 5a.

Subsequently, in the next step, \( \varepsilon_1 \) is replaced with \( \varepsilon_{\text{eff}} (h_2) \) and then \( \varepsilon_{\text{eff}} (h_3) \) is determined for a given \( \Delta h_1 \) by employing the technique in [19]. The obtained results are given in Table 12. It should be noted that the thickness of layer 1 in Tables 5 and 12 is limited to 0.2–0.4 mm considering the practical scenarios/applications. However, woolen and felt jackets are in general thick and therefore the thickness of 1–1.5 mm are used in the analysis. It is clear that the variations...
TABLE 7. Comparison of simulated and theoretically obtained resonant frequencies of the MPA covered by two superstrate layers in this work with [21] (Case 1: $\varepsilon_1 = \varepsilon_2 < \varepsilon_3$, where $\varepsilon_1 = \varepsilon_2 = 3.66$, and $\varepsilon_3 = 4.7$) [\(\Delta h_1 = h_3 - h_2, \Delta h = h_2 - h_1, L = 31.5\) mm, \(W = 41.3\) mm].

| $\Delta h_1$ (mm) | $\Delta h$ (mm) | $d_{\text{eff}}$ [21] | $d_{\text{eff}}(h_2)$ [Prop.] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | %var. [21] | %var. [Prop.] |
|------------------|-----------------|-------------------------|-------------------------------|------------------------|-----------------------|-------------------------|-----------|-------------|
| 1.0              |                 | 3.527                   | 3.995                         | 2.302                  | 2.393                 | 2.300                   | 3.95      | 0.08        |
|                  | 0.5             | 3.544                   | 4.056                         | 2.296                  | 2.387                 | 2.280                   | 3.96      | 0.70        |
|                  | 1.0             | 0.5                     | 3.579                         | 4.191                  | 2.283                  | 2.376                   | 2.245     | 4.07        |
|                  | 1.5             | 0.5                     | 3.551                         | 4.044                  | 2.290                  | 2.391                   | 2.288     | 4.41        |
|                  | 2.5             | 0.5                     | 3.587                         | 4.240                  | 2.272                  | 2.373                   | 2.234     | 4.49        |
| 2.0              | 1.5             | 0.5                     | 3.545                         | 4.140                  | 2.270                  | 2.387                   | 2.260     | 5.15        |
|                  | 2.5             | 0.5                     | 3.564                         | 4.222                  | 2.262                  | 2.381                   | 2.240     | 5.26        |
|                  |                 | 3.602                   | 4.343                         | 2.250                  | 2.368                   | 2.210                   | 5.43      | 1.70        |

TABLE 8. (Case 2: $\varepsilon_1 = \varepsilon_2 > \varepsilon_3$, where $\varepsilon_1 = \varepsilon_2 = 3.66$, and $\varepsilon_3 = 2.2$).

| $\Delta h_1$ (mm) | $\Delta h$ (mm) | $d_{\text{eff}}$ [21] | $d_{\text{eff}}(h_3)$ [Prop.] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | %var. [21] | %var. [Prop.] |
|------------------|-----------------|-------------------------|-------------------------------|------------------------|-----------------------|-------------------------|-----------|-------------|
| 1.0              |                 | 3.508                   | 3.988                         | 2.314                  | 2.400                 | 2.305                   | 3.72      | 0.40        |
|                  | 0.5             | 3.519                   | 4.058                         | 2.305                  | 2.396                 | 2.286                   | 3.94      | 0.82        |
|                  | 1.0             | 0.5                     | 3.538                         | 4.170                  | 2.284                  | 2.390                   | 2.255     | 4.64        |
|                  | 1.5             | 0.5                     | 3.511                         | 4.038                  | 2.311                  | 2.398                   | 2.291     | 3.77        |
|                  | 2.5             | 0.5                     | 3.522                         | 4.120                  | 2.300                  | 2.395                   | 2.270     | 4.13        |
| 2.0              | 1.5             | 0.5                     | 3.542                         | 4.211                  | 2.282                  | 2.388                   | 2.243     | 4.70        |
|                  | 2.5             | 0.5                     | 3.517                         | 4.152                  | 2.300                  | 2.396                   | 2.264     | 4.17        |
|                  |                 | 3.548                   | 4.301                         | 2.262                  | 2.386                   | 2.222                   | 5.48      | 1.80        |

achieved by the combined technique is significantly lower when compared to the approach reported in [21].

VI. MEASURED RESULTS

Two MPAs, given in Figs. 6(a) and (b), operating at 2.38 GHz using parameters in Tables 1 and 6 are prototyped to validate the presented theory. The dielectric layers RO4350B, RO5880, and FR4 to be used as superstrate of identical size are also fabricated. The successive layers of the superstrates are positioned one after another and stacked together over the MPA with the help of low permittivity adhesive RTV coating ($\varepsilon_r = 1.22$). For the MPA covered with textiles, measurement of $f_r$ in VNA is carried out by placing either single or multiple layers over it. The results in the form of plot is given for some cases while the detailed results are provided in tables.

A. SINGLE SUPERSTRATE AND TEXTILE OVER MPA

The measurement for the first two rows of Table 2 are shown in Figs. 7(a)-(b). The MPA covered with a single layer of RO4350B of $h = 1.524$mm is given in Fig. 7(a) whereas measurement of MPA covered with two layers of RO4350B having combined height of 3.048mm is depicted in Fig. 7(b). It is important to take care while applying the adhesive (RTV coating) on the dielectric layer so that no air gap is formed at the interface. Moreover, sufficient space is left at the feed location to suitably place the dielectric layers over the MPA in the presence of SMA connectors in both Figs. 7(a)-(b). The plot in Fig. 7(c) depicts measured $f_r$ of uncovered along with superstrate covered MPA for all the thicknesses mentioned in Table 13. The selection of $\Delta h$ in Tables 13–15 are regulated by the availability of resources for in-house fabrication. Moreover, the values of $\Delta h$ in Tables 13–15 for measurement of $f_r$ may differ from the values used for the determination of theoretical $f_r$. For example, for $\Delta h = 1.524$mm, the step III of
TABLE 9. (Case 3: $\varepsilon_1 < \varepsilon_2 > \varepsilon_3$, where $\varepsilon_1 = 3.66$, $\varepsilon_2 = 4.7$ and $\varepsilon_3 = 2.2$).

| $\Delta h$ (mm) | $\Delta h$ (mm) | $\varepsilon_{ef}$ [21] | $\varepsilon_{ef}(h)$ [Prop.] | $\varepsilon_{m}(h)$ [Prop.] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | %var. [21] | %var. [Prop.] |
|-----------------|-----------------|------------------------|-----------------------------|----------------------------|-----------------------|----------------------|------------------------|-------------|-------------|
| 1.0             | 1.0             | 3.511                  | 3.990                       | 2.295                      | 2.398                 | 2.302                | 4.50                   | 0.35        |             |
| 1.5             | 2.5             | 3.515 3.840            | 4.058                       | 2.294                      | 2.307                 | 2.284                | 4.77                   | 0.04        | 0.44        |
| 2.5             |                 | 3.520                  | 4.160                       | 2.285                      | 2.375                 | 2.250                | 5.43                   | 0.62        |             |

TABLE 10. (Case 4: $\varepsilon_1 > \varepsilon_2 < \varepsilon_3$, where $\varepsilon_1 = 3.66$, $\varepsilon_2 = 2.2$ and $\varepsilon_3 = 4.7$).

| $\Delta h$ (mm) | $\Delta h$ (mm) | $\varepsilon_{ef}$ [21] | $\varepsilon_{ef}(h)$ [Prop.] | $\varepsilon_{m}(h)$ [Prop.] | Sim. Freq. (GHz) (CST) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | %var. [21] | %var. [Prop.] |
|-----------------|-----------------|------------------------|-----------------------------|----------------------------|-----------------------|----------------------|------------------------|-------------|-------------|
| 1.0             | 1.0             | 3.515 3.833            | 4.056                       | 2.320                      | 2.385                 | 2.310                | 3.23                   | 0.43        |             |
| 1.5             | 1.5             | 3.533 3.925            | 4.135                       | 2.315                      | 2.383                 | 2.287                | 3.28                   | 1.18        |             |
| 1.5             | 1.0             | 3.521 3.925            | 4.172                       | 2.311                      | 2.392                 | 2.288                | 3.50                   | 1.00        |             |
| 2.5             |                 | 3.543                  | 4.251                       | 2.302                      | 2.388                 | 2.266                | 3.73                   | 1.55        |             |
| 2.5             |                 | 3.567                  | 4.324                       | 2.292                      | 2.380                 | 2.250                | 3.84                   | 1.80        |             |

the proposed model determines $\varepsilon_{ef}$ and $f_r$ for the modified $\Delta h$ of 1.5mm. Similarly, theoretical $f_r$ are determined for modified $\Delta h$ of 3.4.6, 1.6, 3.2 and 4.7mm for the respective $\Delta h = 3.048, 4.572, 1.575, 3.15, and 4.725$mm. As a consequence, the proposed underestimates or overestimates the eventual $\varepsilon_{ef}$ and $f_r$. But it is apparent from the data in Tables 13-15 that the measured/simulated and theoretical results show excellent agreement despite the presence of slight anomaly in the selection of $\Delta h$.

To evaluate the proposed technique for practical applications such as on-body communication, similar steps for measuring $f_r$ of MPA covered with single felt fabric layer is developed as shown in the measurement setup of Fig. 8(a). During the measurement with textiles, formation of air gap between its layer and MPA is avoided by taking appropriate care. For this, a layer of textile is pressed over the MPA with considerable force at the bottom. Therefore, this work restricts its analysis to textiles over MPA without air gap. However, in the presence of SMA connector and cable, bulge appears due to air gap as can be seen in Fig. 8(a). This air gap, however, has very little impact considering that majority of the radiation takes place near the patch which is well covered by the textile layer. The measured results for all the textile layers, given in Table 16, show very good agreement with the theoretical values in Table 5. In addition, the measured values of $f_r$ in Fig. 8(b) for the MPA covered with wool, jeans cotton, and polyester with the respective $\Delta h$ of 1.5, 0.3, and 0.3 mm clearly show that these are very close with that of theoretical values.

### B. Effectiveness of the Proposed Model to Restore $f_r$

The original $f_r$ can be restored by altering the length once the $\varepsilon_{ef}$ for a given superstrate over the MPA is determined. For this, the determined $\varepsilon_{ef}$ from the proposed model becomes the new permittivity of the design to recalculate new physical parameters of the MPA. The condition in row 3 of the Table 2 is used to elaborate this aspect. For the parameters in the Table 2, the $\varepsilon_{ef}$ is 4.1277 and this is used to compute the modified length of the MPA. In order to restore the original $f_r$ i.e. 2.38GHz, the modified length is given by (15). Here, $L^m$ is the modified length of the MPA.

$$f_r = \frac{c}{2(L^m + \Delta L)\sqrt{\varepsilon_{ef}}}$$

The substitution of known values of $f_r$, $\varepsilon_{ef}$, $c$, and $\Delta L$ in (15) results in $L^m$ of 29.37mm. The MPA resonates at 2.392GHz, as depicted in Fig. 7(c), for the newly computed length. The shift in frequency from the original can be attributed to the overestimation of $\varepsilon_{ef}$ by the model. This implies that for the chosen case, the obtained $f_r$ from the model is lower than the simulated $f_r$ as is evident from Table 2 due to overestimation of $\varepsilon_{ef}$. Apparently, substitution of this $\varepsilon_{ef}$ in (15) results in smaller $L^m$ than the desired length.
TABLE 11. (Case 5: $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$, where $\varepsilon_1 = 4.7$, $\varepsilon_2 = 3.66$ and $\varepsilon_3 = 2.2$) ($L = 27.7$ mm, $W = 38.5$ mm).

| $\Delta h_1$ (mm) | $\Delta h$ (mm) | $\varepsilon_{\text{eff}}$ [21] | $\varepsilon_{\text{eff}}(h_1)$ [Prop.] | $\varepsilon_{\text{eff}}(h_2)$ [Prop.] | Sim. Freq. (GHz) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | $\%\text{var.}$ [21] | $\%\text{var.}$ [Prop.] |
|------------------|-----------------|----------------------|------------------------|------------------------|-----------------|---------------------|---------------------|-----------------|-----------------|
| 1.0              | 4.471           | 4.895                | 2.317                  | 2.391                  | 2.300           | 3.20                | 0.56                |
|                  | 4.482           | 5.021                | 2.292                  | 2.385                  | 2.300           | 4.00                | 0.35                |
| 1.5              | 4.475           | 4.942                | 2.312                  | 2.390                  | 2.318           | 3.37                | 0.26                |
| 1.5              | 4.486           | 4.976                | 2.305                  | 2.387                  | 2.311           | 3.56                | 0.25                |
| 2.5              | 4.503           | 5.056                | 2.290                  | 2.382                  | 2.293           | 4.02                | 0.13                |
|                  | 4.481           | 5.003                | 2.310                  | 2.388                  | 2.298           | 3.38                | 0.52                |
|                  | 4.492           | 5.050                | 2.300                  | 2.386                  | 2.288           | 3.74                | 0.53                |
|                  | 4.512           | 5.124                | 2.285                  | 2.380                  | 2.269           | 4.16                | 0.70                |

TABLE 12. Comparison of simulated and theoretically obtained resonant frequencies of the MPA covered by two textile layers as superstrate layers in this work with [21].

| Layer 1       | Layer 2       | $\Delta h_1$ (mm) | $\Delta h$ (mm) | $\varepsilon_{\text{eff}}$ [21] | $\varepsilon_{\text{eff}}(h_1)$ [Prop.] | $\varepsilon_{\text{eff}}(h_2)$ [Prop.] | Sim. Freq. (GHz) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | $\%\text{var.}$ [21] | $\%\text{var.}$ [Prop.] |
|---------------|---------------|-------------------|-----------------|----------------------|------------------------|------------------------|-----------------|---------------------|---------------------|-----------------|-----------------|
| Polyester     | Terry wool    | 0.2               | 1.0             | 3.471                | 3.622                  | 2.368                  | 2.4119          | 2.387               | 1.85                | 0.80            |
|               |               | 0.3               | 1.0             | 3.472                | 3.640                  | 2.365                  | 2.4116          | 2.381               | 1.88                | 0.60            |
| Jeans cotton  | Terry wool    | 0.3               | 1.0             | 3.473                | 3.660                  | 2.364                  | 2.4113          | 2.375               | 2.00                | 0.46            |
|               |               | 0.4               | 1.0             | 3.474                | 3.663                  | 2.362                  | 2.4109          | 2.375               | 2.06                | 0.55            |
| Pure cotton   | Felt          | 0.2               | 1.0             | 3.471                | 3.678                  | 2.360                  | 2.4105          | 2.370               | 2.14                | 0.42            |
|               |               | 0.3               | 1.0             | 3.472                | 3.640                  | 2.365                  | 2.4115          | 2.381               | 1.97                | 0.68            |
| Rayon         | Felt          | 0.2               | 1.0             | 3.475                | 3.623                  | 2.362                  | 2.4104          | 2.387               | 2.05                | 1.06            |
|               |               | 0.3               | 1.0             | 3.476                | 3.644                  | 2.358                  | 2.4102          | 2.380               | 2.21                | 0.93            |

TABLE 13. Comparison of measured and theoretically obtained resonant frequencies of the MPA for superstrate of permittivity $\varepsilon_2 = 3.66$ (case 1: $\varepsilon_1 = \varepsilon_2$).

| $\Delta h$ (mm) | Meas. Freq. (GHz) | $\%\text{var.}$ [19] | $\%\text{var.}$ [20] | $\%\text{var.}$ [Prop.] |
|-----------------|------------------|---------------------|---------------------|------------------------|
| 1.524           | 2.302            | 3.55                | 5.15                | 0.43                   |
| 3.048           | 2.290            | 3.42                | 5.50                | 0.96                   |
| 4.572           | 2.262            | 4.25                | 6.80                | 1.85                   |

TABLE 14. Comparison of measured and theoretically obtained resonant frequencies of the MPA for superstrate of permittivity $\varepsilon_2 = 2.2$ (case 2: $\varepsilon_1 > \varepsilon_2$).

| $\Delta h$ (mm) | Meas. Freq. (GHz) | $\%\text{var.}$ [19] | $\%\text{var.}$ [20] | $\%\text{var.}$ [Prop.] |
|-----------------|------------------|---------------------|---------------------|------------------------|
| 1.575           | 2.338            | 2.40                | 4.40                | 1.25                   |
| 3.150           | 2.327            | 2.06                | 4.70                | 1.80                   |
| 4.725           | 2.312            | 2.00                | 5.23                | 3.24                   |

TABLE 15. Comparison of measured and theoretically obtained resonant frequencies of the MPA for superstrate of permittivity $\varepsilon_2 = 4.7$ (case 3: $\varepsilon_1 < \varepsilon_2$).

| $\Delta h$ (mm) | Meas. Freq. (GHz) | $\%\text{var.}$ [19] | $\%\text{var.}$ [20] | $\%\text{var.}$ [Prop.] |
|-----------------|------------------|---------------------|---------------------|------------------------|
| 1.5             | 2.290            | 4.41                | 5.76                | 0.66                   |
| 3.0             | 2.262            | 4.80                | 6.50                | 0.53                   |
| 4.5             | 2.245            | 4.80                | 6.95                | 1.56                   |

to bring resonance at 2.38 GHz. Thus it can be inferred that the smaller variation leads to higher accuracy in the determination of $L_m$ and hence better accuracy in the restoration of the original $f_0$. It is imperative to note that only the length in the above discussion is modified while keeping the width unchanged and as a result the return loss is poor as can be seen in Fig. 7(c).

C. TWO SUPERSTRATE AND TEXTILE OVER MPA

The $f_0$ for the combination of superstrates, listed in Tables 7–11, over the MPA are measured. The measurement setup with successive layers of superstrates over the MPA is similar to Fig. 7(a)-(b) with the only difference being the stacking of distinct second layer. The measurement results for some of the $\Delta h_1$ and $\Delta h$ covering all five cases in section V
are given in Table 17. An MPA on FR4 substrate is prototyped for the parameters given in Table 6 to measure case 5 of Table 17. Apparently, the variations in \( f_r \) are in good agreement with the predicted values in section V. This validates the effectiveness of the proposed model for two dielectric layers over the MPA.

Subsequently, the MPA is covered with the combination of textile layers mentioned in Table 12 and the values of \( f_r \) are measured using the setup given in Fig. 8a. The Table 18 includes the measured \( f_r \) for some of the combinations. The chosen thickness of the textile layers in this work is the average of many samples. It is once again clear that the measured variation in \( f_r \) perfectly agrees with the predicted values in Table 12 and therefore demonstrate the scalability of the proposed model to two superstrate layers.

**TABLE 16.** Comparison of measured and theoretically obtained resonant frequencies of the MPA covered with single textile superstrates.

| Material      | \( \varepsilon_r \) | \( \Delta h^* \) (mm) | Meas. Freq. (GHz) | \%var. [19] | \%var. [20] | \%var. [Prop.] |
|---------------|----------------------|------------------------|-------------------|-------------|-------------|----------------|
| Polyester     | 1.40                 | 0.3                    | 2.375             | 1.46        | 2.84        | 0.40           |
| Jeans cotton  | 1.60                 | 0.3                    | 2.373             | 1.50        | 2.91        | 0.46           |
| Pure cotton   | 1.70                 | 0.2                    | 2.371             | 1.61        | 3.00        | 0.17           |
| Rayon         | 3.20                 | 0.2                    | 2.367             | 1.73        | 3.00        | 0.15           |
| Felt fabric   | 1.22                 | 1.5                    | 2.363             | 1.46        | 3.35        | 2.64           |
| Terry wool    | 1.30                 | 1.5                    | 2.358             | 1.45        | 3.54        | 2.44           |
| Leather       | 1.66                 | 1.5                    | 2.359             | 1.32        | 3.36        | 2.50           |

**TABLE 17.** Comparison of measured and theoretically obtained resonant frequencies of the MPA covered with two superstrate layers.

| Case          | \( \Delta h^1 \) (mm) | \( \Delta h \) (mm) | Meas. Freq. (GHz) | \%var. [21] | \%var. [Prop.] |
|---------------|------------------------|---------------------|-------------------|-------------|----------------|
| \( \varepsilon_1 = \varepsilon_2 < \varepsilon_3 \) | 1.500                   | 1.524               | 2.286             | 4.33        | 0.83           |
| \( \varepsilon_1 = \varepsilon_2 > \varepsilon_3 \) | 1.575                   | 1.524               | 2.302             | 4.04        | 1.40           |
| \( \varepsilon_1 = \varepsilon_2 \) | 1.575                   | 1.500               | 2.290             | 4.50        | 0.87           |
| \( \varepsilon_1 > \varepsilon_2 < \varepsilon_3 \) | 1.500                   | 1.575               | 2.318             | 3.15        | 1.34           |
| \( \varepsilon_1 > \varepsilon_2 = \varepsilon_3 \) | 1.575                   | 1.524               | 2.307             | 3.47        | 0.17           |

**TABLE 18.** Comparison of measured and theoretically obtained resonant frequencies of the MPA covered with two textile layers.

| Layer 1 | Layer 2 | \( \Delta h_1 \) (mm) | \( \Delta h \) (mm) | Meas. Freq. (GHz) | \%var. [21] | \%var. [Prop.] |
|---------|---------|------------------------|---------------------|-------------------|-------------|----------------|
| Polyester | Wool    | 0.3                    | 1.5                | 2.3708             | 1.71        | 0.18           |
| Jeans cotton | Wool    | 0.3                    | 1.5                | 2.3628             | 2.04        | 0.52           |
| Pure cotton | Felt    | 0.2                    | 1.5                | 2.3668             | 1.85        | 0.60           |
| Rayon   | Felt    | 0.2                    | 1.5                | 2.3547             | 2.33        | 1.07           |

**D. MULTI-TEXTILE LAYER OVER MPA**

Next the effectiveness of the proposed theory for multi-layered superstrate structures over the MPA is demonstrated, using identical measurement to Fig. 8a, with a combination of polyester, foam, and polyester (typically a windcheater). The polyester form layers 1 and 3 whereas layer 2 consists of foam. No air gap between the successive layers in simulation as well as in measurement is considered. The thickness of foam and polyester is takes as 1.2mm and 0.3mm while the corresponding permittivities are 1.13 and 1.4 in both the simulation and measurement scenarios. The presence of third superstrate layer of thickness \( \Delta h_4 \) makes the parameter \( \Delta h_2 = h_3 - h_4 \). Then \( f_r \) is determined using the steps in sections III and V for the combinations mentioned in Table 19. The comparison between the theoretical, simulated, and measured \( f_r \) for the proposed technique
shows excellent consonance. In addition, the variation for the proposed technique is substantially smaller when compared to the results obtained using technique reported in [21]. The obtained results also demonstrate that the proposed model and formulations is scalable with extremely good accuracy to the situations when MPA is covered with multiple layers on it therefore significantly advances the existing state-of-the-art.

VII. CONCLUSION
A novel iterative model along with a new empirical relation to determine \( \varepsilon_{\text{eff}} \) and \( f_r \) of MPA covered with multiple dielectric layers is reported in this paper. The formulation of \( \varepsilon_{\text{eff}} \) is based on series–parallel combination of dielectric loaded capacitors between the metallic patch and the ground plane. The estimation of shift in \( f_r \), a posteriori is desired in wireless body area network for achieving desired reliability. It is well accepted that a reliable link to transfer essential physiological parameters to an external node is essential considering that no loss of data should take place due to out-of-band communication between transmitter and receiver. To facilitate this, the presented model determines \( \varepsilon_{\text{eff}} \) for substrate and the first superstrate layer. The process is then repeated by replacing \( \varepsilon_1 = \varepsilon_{\text{eff}} \) for the successive superstrate layers and this ultimately results in \( \varepsilon_{\text{eff}} \) and \( f_r \) for the whole structure. The model then determines \( f_r \) of MPA covered with single superstrate layer for the three cases of \( \varepsilon_1 = \varepsilon_2 \), \( \varepsilon_1 > \varepsilon_2 \) and \( \varepsilon_1 < \varepsilon_2 \). The small variations in the measured and simulated \( f_r \) for the proposed model for the three cases suggest that the model is very good for dielectric cover of \( \varepsilon_2 > 2.2 \). Furthermore, the proposed model when tested on MPA covered with textile layers shows excellent performance for thinner heights and a slightly weaker performance for thicker superstrates. The application of the proposed model on MPA covered with two superstrate layers for \( \varepsilon_1 = \varepsilon_2 > \varepsilon_3, \varepsilon_1 = \varepsilon_2 < \varepsilon_3, \varepsilon_1 < \varepsilon_2 > \varepsilon_3, \varepsilon_1 = \varepsilon_2 < \varepsilon_3, \varepsilon_1 < \varepsilon_2 > \varepsilon_3, \varepsilon_1 > \varepsilon_2 < \varepsilon_3, \) and \( \varepsilon_1 > \varepsilon_2 > \varepsilon_3 \) respectively shows outstanding result with lower variations when compared to the state-of-the-art techniques. It is also shown that the proposed model when employed in conjunction with an existing technique significantly advances the state-of-the-art. In brief, the proposed model has lower complexity and therefore has the potential for easy incorporation with any technical computing software.

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TABLE 19. Comparison of simulated, measured and theoretically obtained resonant frequencies of the MPA covered by three textile layers as superstrate (Wind Cheater) in this work with [21].

| Layer 1 | Layer 2 | Layer 3 | \( d_h \) (mm) | \( \Delta h_r \) (mm) | \( \Delta h_l \) (mm) | Sim. Freq. (GHz) | Meas. Freq. (GHz) | Th. Freq. (GHz) [21] | Th. Freq. (GHz) [Prop.] | %var. [%var. [Prop.] | %var. [%var. [Prop.]] | %var. [%var. [Prop.]] | %var. [%var. [Prop.]] |
|---------|---------|---------|----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Poly ester | Foam | Poly ester | 0.3 | 1.2 | 0.3 | 2.374 | 2.375 | 2.410 | 2.381 | 1.52 | 0.30 | 1.47 | 0.25 |

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