Optimization-Based Matching Layer Design for Broadband Dielectric Lens Antennas

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Abstract **─** Dielectric lens antennas fabricated with a dense dielectric material, allow good power transfer efficiency through the lens and enable fabrication of low-cost and compact-size lens antennas. On the contrary, using dense dielectric material causes strong multiple internal reflection behavior inside the lens antenna. These multiple reflections deteriorate not only return loss but also the radiation characteristics. However, the undesirable effects of strong internal reflections can be reduced considerably using one or more dielectric Matching Layers (MLs) coated at the top of the antenna. In this paper, a novel optimization-based ML design procedure for dielectric lens antennas is proposed. In order to demonstrate effectiveness of the method, the optimization procedure is applied to two different dielectric lens antennas; a narrow band lens antenna and an Ultra-Wideband (UWB) lens antenna. The simulation results verify that MLs designed by the proposed optimization procedure prevent strong internal reflections successfully for both narrow-band and UWB applications.

Index Terms **─** Air-gap, dielectric lens antennas, matching layer, optimization, and UWB antennas.

I. INTRODUCTION

Dielectric lens antennas are widely used in millimeter-wave and sub-millimeter-wave applications, due to the fact that these antennas have high directivity, polarization purity and simple structure for fabrication [1-5]. Dielectric lens antennas are inexpensive solutions for beam steering applications with their capability of being integrated to millimeter and sub-millimeter planar feeding structures [6-7]. Mentioned characteristics make dielectric lens antennas a good candidate also for passive imaging systems and active automotive cruise control radars [8-10]. In these applications, relative permittivity of the lens material should be chosen carefully, since materials having low or high dielectric contrast with free space, have distinctive effects on the radiation characteristics of the antenna.

Low-permittivity $(\varepsilon_r < 3)$, low-loss materials are affordable solutions for dielectric lenses, which can be easily manufactured with standard tools. On the other hand, high-permittivity materials yield a more exact geometrical approximation to an elliptical lens and achieve a wider multiple-beam coverage range [11]. Typically, when the relative permittivity of the selected lens material is higher than three, considerable amounts of internal reflections occur at the dielectric-air interface [12-13]. The amount of internal reflections due to the dielectric contrast with free space, increase dramatically with the increment of dielectric contrast. For example, transmitted power ratios from dielectric-air interface are 0.96, 0.82, 0.76 and 0.54 for the materials Teflon $(\varepsilon_r = 2.25)$, Macor $(\varepsilon_r = 6)$, Alumina $(\varepsilon_r = 8.5)$ and Silicon $(\varepsilon_r = 11)$, respectively. These ratios are calculated for a flat and infinite interface, which is illuminated by a normal incident plane wave.

These internal reflections disrupt not only return loss but also the radiation characteristics of the antenna. In literature, the effects of internal reflections on radiation properties and input impedance of integrated lens antennas, are investigated in details [12-14]. If these reflections can be eliminated significantly, using high

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permittivity lens material will present many benefits, such as effective power transfer through the lens and consequently low SLL and high directivity for the antenna designer.

Most common ways of reducing the internal reflections are using corrugations [15] or ML(s) made of homogeneous dielectric materials on the lens surface [16-17]. In [18], influences of dielectric matching layers on the radiation characteristics are investigated and concluded that choosing an appropriate ML improves the frequency stability of the main beam, reduces the average SLL and enhances the gain of the lens antenna.

However, when the MLs are designed using standard $\lambda_c/4$ matching rules, where λ_c is the wavelength in dielectric at the operating frequency, there are some points that are not considered:

i) Relative permittivity values of the materials calculated using standard $\lambda_c/4$ matching rules probably does not exist. Although, this is not a negation in theory, in practical applications materials having approximate relative permittivity values to calculated values has to be used and this will result in unexpected radiation characteristics.
ii) More importantly, if quarter wavelength MLs are designed, these MLs will be useful only at the corresponding operating frequency.

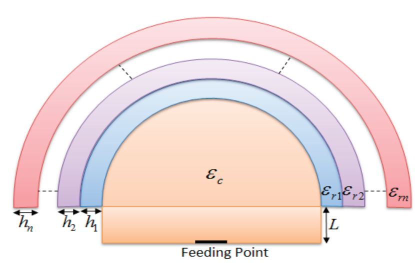
In this work, an optimization-based matching layer design procedure for broadband dielectric lens antennas is introduced. The lens structure and matching layers are modelled as a cascaded transmission line and maximum amount of power transfer is aimed from feed to the air. With this purpose, the relative permittivity values of the materials and the thicknesses of the MLs are optimized using Genetic Algorithms (GA). The details of the optimization process are described in section II. To demonstrate the effectiveness of the proposed design method, the method is applied to two different dielectric lens antennas from literature. The first one was designed for active or passive automotive radar applications operating at 77 GHz frequency, where the second one is a leaky-wave dielectric lens antenna operating in ultra-wide frequency band (4-12 GHz). The geometrical descriptions of both antennas are given in section III together with their feeding structure. The radiation characteristics of the lens antennas with and without MLs are demonstrated in section IV. The radiation patterns of the antennas are simulated by the CST commercial tool [19]. The key roles of using an optimization based ML design in UWB applications are also discussed.

When MLs are coated to the surface of a lens antenna, a thin parasitic air gap remains between the dielectric materials. Nevertheless, to the best of my knowledge the influence of remaining air gap between the dielectric materials has never been studied. In the fourth section, the effects of air gaps on internal reflections are also exhibited. The considerations on the results are given in the last section.

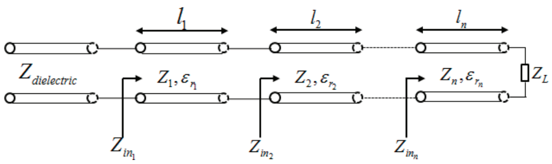
II. OPTIMIZATION METHODOLOGY

Although, using high permittivity dielectric materials for lens antennas has many advantages, it causes strong internal reflections inside the lens. These reflections have to be reduced considerably to form the expected radiation characteristics. Common way to eliminate the negative effects of internal reflections is to place one or more dielectric matching layers at the top of the antenna. Determination of the relative permittivity and physical dimensions of the coating materials is crucial to obtain expected contribution of the MLs on the radiation.

Rather than using standard $\lambda_c/4$ matching rules where MLs operate effectively only at a single frequency, in this work, a novel optimization-based ML design procedure valid for broadband applications as well is proposed. This is achieved by composing a transmission line model for dielectric lens antennas having cascaded MLs. This concept is introduced with Fig. 1. In Fig. 1 (a), an extended hemispherical lens antenna having multiple MLs is shown. In Fig. 1 (b), the corresponding transmission line model for this configuration is demonstrated.



(a)



(b)

Fig. 1. The dielectric lens antenna having multiple MLs: (a) geometrical representation and (b) cascaded transmission line model.

Using the cascaded transmission line model, the general reflection coefficient from the interface of the lens antenna and MLs can be formulated as follows:

$$\Gamma = \frac{\left|Z_{in_n} - Z_{dielectric}\right|}{Z_{in_n} + Z_{dielectric}}, \text{ n=1,2,…}N, \qquad (1)$$

where, $Z_{dielectric} = Z_0 / \sqrt{\varepsilon_c}$. Here, N is the number of matching layers and Z_{in_n} is the input impedance of the related ML. Besides, ε_c represents the relative permittivity of the lens material, where ε_0 and μ_0 are permittivity and permeability of free space, respectively. Input impedance of each transmission line given in (1) can be formulated as follows:

$$Z_{in_n} = Z_n \frac{Z_{in_{n+1}} + jZ_n \tan \beta_n l_n}{Z_n + jZ_{in_{n+1}} \tan \beta_n l_n}, \text{ n=1,2,…}N. \qquad (2)$$

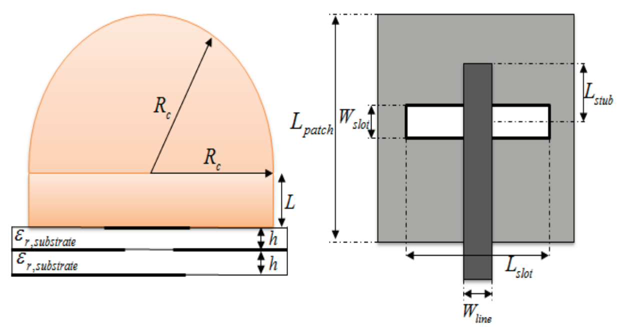
Here, Z_n is the characteristic impedance of the related transmission line, where, β_n and l_n are the phase constant and length of the corresponding transmission line, respectively. When equations (1) and (2) are investigated, it is clear that the design parameters which can be used to minimize the internal reflections from the interface of lens material-MLs are relative permittivity of MLs, $\varepsilon_{r_1}, \varepsilon_{r_2} .. \varepsilon_{r_n}$, (n=1,2,…N) and length of the transmission lines, $l_1, l_2 .. l_n$, (n=1,2,…N). To maximize the power transmission from lens to open air for a cascaded system as given in Fig. 1, the following fitness function is proposed:

$$Fitness = \sum_{f=f_l}^{f_h} \Gamma_f \ . \qquad (3)$$

In (3), f_l and f_h are lowest and highest operating frequencies of the dielectric lens antenna, respectively. By using this fitness function, the reflection coefficient from the lens material to MLs can be minimized for both narrow and broad operating frequencies.

III. ANTENNA CONFIGURATIONS AND FEEDING DETAILS

Two extended hemispherical lens antennas are utilized to demonstrate the effectiveness of the proposed optimization procedure. The extended hemispherical lenses are most popular dielectric lens antennas, since their geometry yields a more exact geometrical approximation to an elliptical lens, resulting with a wider multiple-beam coverage range and high gain. The first antenna chosen for the implementation of optimization procedure was designed for automotive radar applications operating at 77 GHz frequency [18]. The primary source of the antenna is an aperture coupled microstrip patch printed on a RT/Duroid 5880 substrate ($\varepsilon_{r,subs} = 2.23$). The cross section view of the antenna is given in Fig. 2 (a) and the general structure of an aperture coupled microstrip patch is given in Fig. 2 (b). Here, the feed is redesigned to radiate into a dense dielectric material ($\varepsilon_c = 9$), $R_c = 6mm$ and $L = 2.34mm$ with the following dimensions: $L_{patch} = 0.6mm$ and $W_{slot} = 0.26mm$.

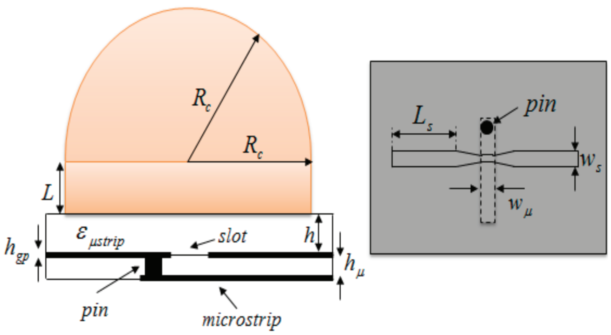


(a) (b)

Fig. 2. Geometry of the primary feed: (a) cross section view and (b) bottom view.

The second dielectric lens antenna structure selected to implement is an UWB leaky lens antenna ($R_c = 46.87mm$, $L = 14.06mm$) [20]. A dense dielectric ($\varepsilon_c = 9.8$) is chosen as the lens material to achieve high gain and high front-to-back ratio. The cross section and bottom views of the structure are given in Fig. 3 (a) and (b), respectively. The feed has been designed to

operate in 4-12 GHz frequency band with the following design parameters:
$W_s = 0.5mm$, $L_s = 38mm$, $h_{gp} = 0.36\mu m$,
$h_\mu = 476mm, h = 937\mu m, w_\mu = 0.26mm, \varepsilon_{\mu,strip} = 3$.



(a) (b)

Fig. 3. Geometry of the UWB lens antenna operating between 4-12 GHz: (a) cross section view and (b) bottom view.

IV. APPLICATION EXAMPLES

In this section, the optimization procedure described in section 2 is applied to the mentioned dielectric lens antennas. Dense dielectric materials $\varepsilon_{c1} = 9$ and $\varepsilon_{c2} = 9.8$ are chosen as lens core for narrow band and UWB antennas, respectively. As given before, more than 25% of the power will be reflected from the dielectric-air interface if the permittivity of the material is higher than 9 ($\varepsilon_c \geq 9$). Thus, in this section, appropriate MLs will be designed for both antennas to reduce the internal reflections significantly, to enlarge the operating frequency band and also to improve the radiation characteristics. The genetic algorithm is utilized for the optimization.

A. Narrow-band application

Although, MLs designed by $\lambda_c/4$ matching rules will be useful for a narrow band antenna, the relative permittivity values of the materials determined will not be realistic for practical applications. Namely, if a single, double or triple MLs are aimed to be designed for a narrow band lens antenna ($\varepsilon_c = 9$) using standard $\lambda_c/4$ matching rules, the relative permittivity and the thickness values of matching materials will be as given in Table 1.

Table 1: Relative permittivity and thicknesses of quarter wavelength MLs

Single ML	Double MLs	Triple MLs
$\varepsilon_1 = 3, h_1 = 0.59mm$	$\varepsilon_1 = 4.32, h_1 = 0.49mm$ $\varepsilon_2 = 2.08, h_2 = 0.71mm$	$\varepsilon_1 = 5.2, h_1 = 0.45mm$ $\varepsilon_2 = 3, h_2 = 0.59mm$ $\varepsilon_3 = 1.73, h_3 = 0.78mm$

These relative permittivity values correspond to some unavailable materials. For practical applications, the material with the calculated relative permittivity should be commercially available. Thus, in this work, to apply the optimization procedure, some commercial materials from Rogers Company are chosen as the ML materials. These are RO4003 ($\varepsilon_r = 3.55$) for a single layer, RT5880 ($\varepsilon_r = 2.2$) and RO3206 ($\varepsilon_r = 6.15$) for double layers and RT5880, RO4003, RO3206 for triple layers. These materials are lossy and the dissipation factors of the materials are approximately 0.002 ($\tan\delta \cong 0.002$). The thicknesses of these MLs are optimized using the given cascaded transmission line model. This is accomplished by modifying the fitness function given by (3) according to considered lens structure and then applying the definitions (1) and (2) into (3).

Optimized thickness values of each MLs are given in Table 2 together with the relative permittivity values. The optimized thickness values that minimize the internal reflections are exhibited in Table 2.

Table 2: Relative permittivity and thickness values of optimized MLs

Single ML	Double MLs	Triple MLs
$\varepsilon_1 = 3.55, h_1 = 2.59mm$	$\varepsilon_1 = 6.15, h_1 = 1.96mm$ $\varepsilon_2 = 2.2, h_2 = 0.66mm$	$\varepsilon_1 = 6.15, h_1 = 0.87mm$ $\varepsilon_2 = 3.55, h_2 = 0.28mm$ $\varepsilon_3 = 2.2, h_3 = 0.36mm$

In case of high dielectric contrast, considerable amount of power will be reflected from dielectric-air interface. This situation is demonstrated in Fig. 4. Return loss (S_{11}) is approximately around -8 dB at 77 GHz frequency. When MLs determined by optimization procedure are placed to the top of the antenna, the return loss values are suppressed to lower than -10 dB within the band of 74-80 GHz. This is also achieved by decreasing the dielectric contrast between the lens core and the outer layer; thus, consequently, minimizing the total internal reflection situations inside the lens. According to Fig. 4, adding MLs also enlarges the operating frequency band of the lens antenna.

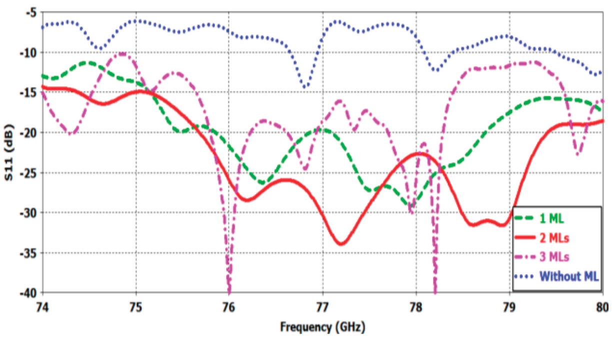
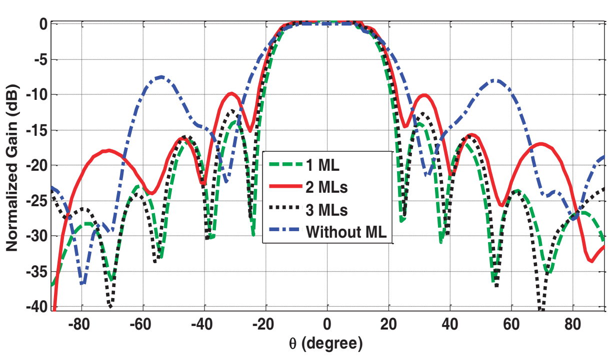
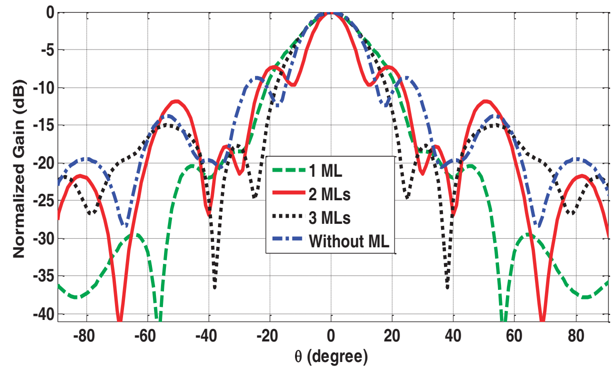


Fig. 4. Return loss variation of the narrow band lens antenna for with and without MLs cases.

The influence of the number of MLs upon the radiation characteristics of the antenna is represented in Fig. 5, in both E and H planes at 77 GHz. The co-polarization components of the antenna in E-plane are given in Fig. 5 (a), where components in H-plane are highlighted in Fig. 5 (b). For without ML case, the SLL is at least 3 dB higher than the other three cases in E-plane and Half Power Beam Width (HPBW) of the radiation pattern is quiet wider than the radiation patterns of the other cases. In Fig. 5 (b), although the SLL in two MLs case is high as without ML case, the HPBW of the pattern is considerably narrower when the antenna is coated by two MLs.



(a)



(b)

Fig. 5. Influence of MLs on the radiation patterns at 77 GHz in: (a) E-plane and (b) H-plane.

B. Ultra-wide band application

The second dielectric lens antenna type utilized to perform the proposed optimization procedure is the UWB leaky lens antenna operating between 4-12 GHz frequencies. The lens core is chosen as a high dielectric material ($\varepsilon_{c2} = 9.8$) and the same dielectric material set (RT5880, RO4003, RO3206) is utilized for MLs. When $\lambda_c/4$ matching rules are used to calculate the thickness of matching layers for a wide band antenna, λ inside the material is accepted at the center frequency. In UWB applications, the wavelengths at the lowest or highest frequencies differ significantly with the wavelength at the center frequency. Thus, MLs designed by $\lambda_c/4$ matching rules will not be applicable for UWB applications, especially for very broadband quasi-optical receivers [21].

The fitness function structure given in (3) is utilized to optimize the thickness values of each case and the results are given together with the relative permittivity values of each material in Table 3.

Table 3: Relative permittivity and thickness values of optimized MLs

Single ML	Double MLs	Triple MLs
$\varepsilon_1 = 3.55, h_1 = 3.97mm$	$\varepsilon_1 = 6.15, h_1 = 3.14mm$ $\varepsilon_2 = 2.2, h_2 = 1.53mm$	$\varepsilon_1 = 6.15, h_1 = 3mm$ $\varepsilon_2 = 3.55, h_2 = 4.11mm$ $\varepsilon_3 = 2.2, h_3 = 2.81mm$

The return loss variation of UWB feed with respect to frequency, is given in Fig. 6. When the lens core is not coated by MLs, the return loss value has some pick points higher than -8 dB between 5-6 GHz and 6-7 GHz frequencies. Although, the level of these picks is reduced by using a single ML or double MLs, the return loss is still higher than -10 dB between 5-6 GHz frequencies. When triple MLs are employed to the top of the lens core, the return loss value is reduced to lower than -10 dB levels in the operating frequency range.

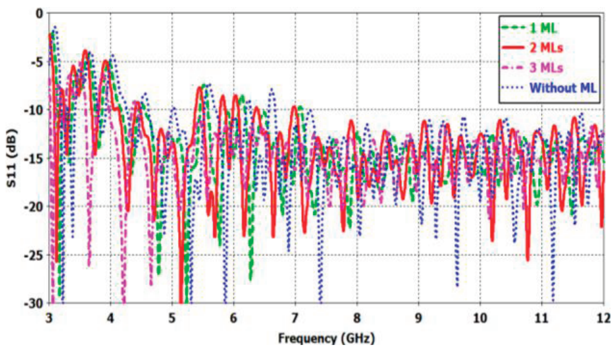
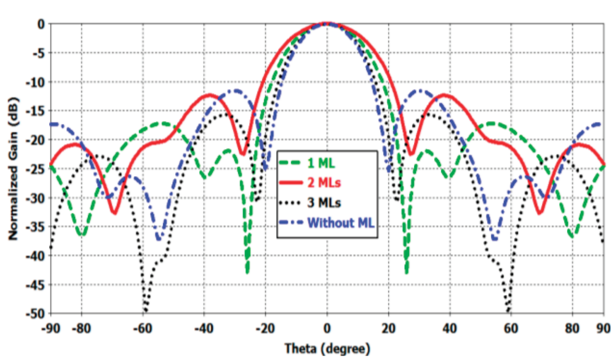
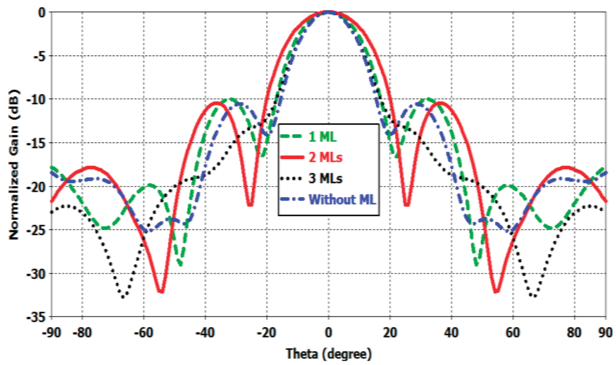


Fig. 6. The return loss variation of the UWB lens antenna for with and without MLs.

With the aim of representing the influence of the number of MLs on the radiation characteristics, far-field radiation paterns are given in both E and H-planes at the center operating frequency (8 GHz) in Fig. 7. According to Fig. 7, in both planes the HPBWs of without ML case and using three MLs case, are narrower than the other two cases. Besides, when three MLs are employed, the SLL is suppressed significantly in H-plane. As a result, covering the lens core with three MLs result in by far the best radiation characteristics among all cases for this UWB application.



(a)



(b)

Fig. 7. Influence of MLs on the UWB dielectric lens antenna patterns at 8 GHz in: (a) E-plane and (b) H-plane.

C. Effects of air-gaps on the radiation characteristics

Adding one or more MLs made of homogeneous dielectric materials on the lens surface is a widely used technique for reducing the internal reflections inside the lens [17]. However, the parasitic air-gap that remains between dielectric materials during the fabrication process is considered as the weakness of this technique. To the best of my knowledge, the influence of parasitic air gaps between the dielectric materials on the radiation characteristics of dielectric lenses has never been studied in the perspective of UWB operation. Thus, CST simulations for UWB leaky wave antenna with three ML case are repeated by considering three different amounts of air-gaps between dielectric materials of the antenna. Three cases with 0.1, 0.2 and 0.5 mm thicknesses are considered. Although, the amounts chosen as air-gaps are quite high for today's fabrication technology, thick air-gaps are preferred to clarify all possible negative effects of air-gaps on the radiation characteristics. The return loss variation of the UWB antenna with three different thicknesses of air-gaps is given in Fig. 8. When the air-gaps between layers are chosen as 0.1 mm, the return loss of the antenna overlaps with the ideal case (no parasitic air-gap). The S_{11} variation for 0.2 mm air gaps is almost same as the S_{11} variation for 0.1 mm air-gaps case. The return loss variation is at reasonable levels for 0.5 mm thickness of air-gaps as well, except 2 dB increment at 5 GHz and 1 dB increment at 5.5 GHz frequencies.

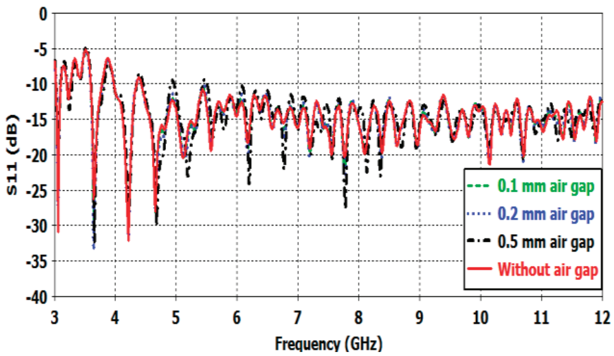
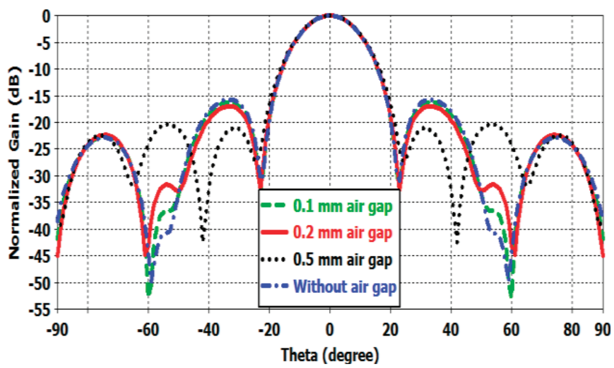
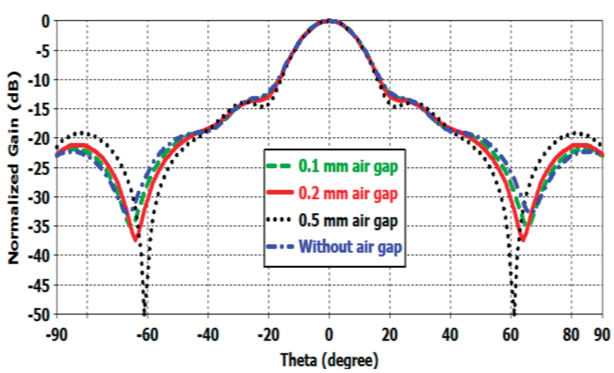


Fig. 8. The return loss variation of UWB lens antenna with three-MLs for with and without air-gaps.

The influence of air-gaps on the radiation patterns of the lens antenna having three-MLs are exhibited in both E and H-planes at 8 GHz frequency. The radiation patterns in E-plane are given in Fig. 9 (a), where H-plane are given in Fig. 9 (b).



(a)



(b)

Fig. 9. Influence of air-gaps on the radiation patterns at 8 GHz frequency in: (a) E-plane and (b) H-plane.

Main and side lobes of the radiation patterns of the antenna in E-plane are not affected considerably with 0.1 mm and 0.2 mm thickness air-gaps between layers, as highlighted in Fig. 9 (a). While the HPBW of the antenna is also conserved with 0.5 mm air-gaps, only the level of second side lobe, which is still in acceptable ranges is increased about 10 dB. Similar comments can be made for the influence of 0.1 mm and 0.2 mm air gap thicknesses on the radiation characteristics in H-plane. As given in Fig. 9 (b), only the level of the outer side lobe is increased a few dB when 0.5 mm parasitic air-gaps remain between dielectric materials. It should also be added that 0.5 mm air-gap thickness is equal to $1/6$ of the lowest ML thickness (see Table 2) in the triple MLs case. For higher frequency applications, 0.5 mm air-gaps will be thick as MLs (see Table 2) and probably will have significant effects on the radiation patterns of the antenna.

V. CONCLUSION

An optimization based matching layer design procedure for broadband dielectric lens antennas is introduced. The lens structure and matching layers are modelled as a cascaded transmission line and maximum amount of power transfer is achieved from feed to the air, by considerably reducing the internal reflections from dielectric-air interface. It has been exhibited that the dielectric lens antenna coated by the MLs designed by proposed method has crucial advantages, namely:

i) For practical applications the material with the calculated relative permittivity should be commercially available. Thanks to proposed method, commercial materials can be chosen as ML materials in the optimization procedure.
ii) More importantly, when the MLs designed by the proposed method will be useful for ultra-wide band applications as well. It should be also emphasized that the radiation characteristics of the dielectric lens antenna, such as directivity, SLL and front-to-back ratio are improved with the optimized MLs in both narrow and wide frequency bands.

These MLs can be fabricated using standard computer aided manufacturing process and the extra cost due to the fabrication of the coating remains acceptable [18]. When the lens surface is coated by MLs, a thin parasitic air gap remains between the dielectric materials. The effects of parasitic air gaps on the radiation characteristics of an UWB antenna are investigated for different air-gap thicknesses. It can be concluded that return loss and radiation characteristics of the antenna are conserved even for 0.5 mm air-gaps, which is quite high for today's fabrication technology.

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