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ORIGINAL ARTICLE

STUDY OF HIGH DIRECTIVITY IN LOWPERMITTIVITY METAMATERIAL SLABS FOR LEAKY-WAVE MODELS

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Abstract:

Investigation has been carried out on the directivity of grounded low–permittivity metamaterial slab structures that achieve highly directive broadside radiation. Two–dimensional (2D) configurations excited by electric line sources are considered, adopting a scalar plasma–like dispersive permittivity for the metamaterial medium that suitably models a wire medium in the presence of a 2D electromagnetic field, with the electric field directed along the wire axes. The role of leaky waves in producing the high directivity attainable with such structures is illustrated by comparing it with a simple ray–optic model for the radiation mechanism.

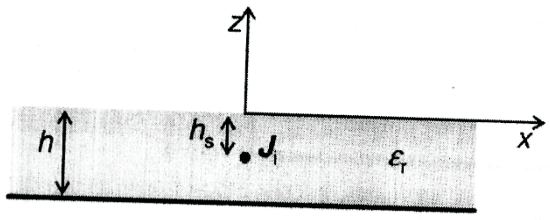
KEYWORDS:

Leaky–wave antennas; Leaky waves; Metamaterials; Planar antennas; wire medium

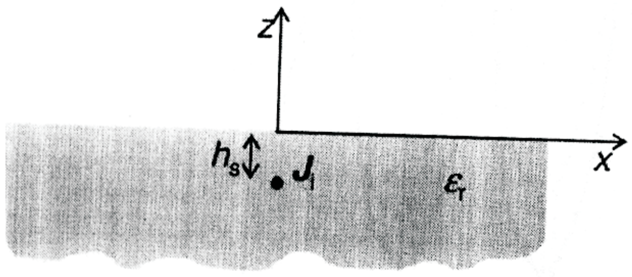
INTRODUCTION

Grounded slabs made of artificial materials (metamaterials) with constitutive parameters exhibiting unusual properties are interesting candidates for planar antennas with enhanced radiative performance. In particular, since the early investigations of Gupta and co-workers, wire-medium slabs have been studied because of their capability to radiate narrow directive beams with simple sources [l—5]. It should he noted that in Ref. 6 the same geometry was analyzed to study the effect of an unwanted plasma layer over a magnetic source, reaching conclusions similar to those in Refs. 1-5. In Ref. 7 the radiation of a source in a metamaterial slab with a small positive permittivity has been compared with more standard Fabry-Perot cavity antennas.

As is well known, a wire medium can be described as an isotropic dielectric with a plasma-like dispersive permittivity for electromagnetic fields that propagate in the plane perpendicular to the wire axis and are polarized TM with respect to the wire axis [8–12]. The ease of oblique incidence requires a more involved anisotropic spatially dispersive model [13]. In Ref. 5, a grounded low-permittivity slab has been studied with an electric line source as an excitation [Fig. 1 (a)]. This configuration can produce a narrow beam at broadside, with an extremely high directivity. Conditions were derived for achieving maximum power density radiated at broadside, and the role of leaky waves in producing the enhanced broadside radiation and the narrow beam was demonstrated. A comparison with a low-permittivity half-space [Fig. 1(b)] was also provided in Ref. 5. Results showed that the half- space configuration could also provide a narrow beam, but not a significantly enhanced power density at broadside. It was also show it that fir the half—space configuration the narrow beam is not due to a leaky mode, hut is the result of a ray-optic tensing type of died.

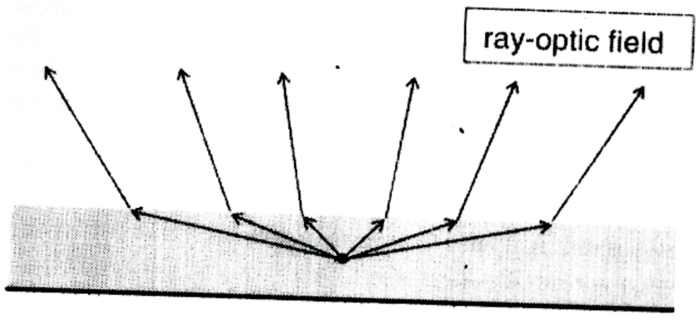


(a)

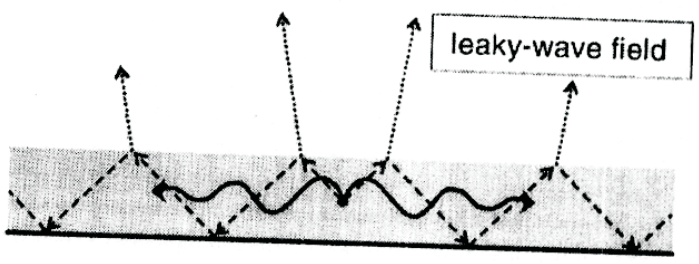


(b)

Figure 1 The low-permittivity structures considered lucre, with the relevant physical and geometrical parameters. (a) A grounded metamaterial dumb with a tine source inside. (b) A metamaterial half–space with a line source inside



(a)



(b)

Figure 2 Radiation mechanisms for the highly directive broadside radiation attainable with the structure in Figure 1 (a) Ray–optic model showing the refractive tensing effect at the top interface. (b) Leaky wave model showing propagating leaky mode that is excited by the line source.

There are two aspects that remain unclear (a) the relative importance of the leaky-wave and ray–optic effects in producing the directivity enhancement for the slab problem. for both optimum and nonoptimum in slab thicknesses, and (b) the manner in which the slab results approach that of the hall-space as the slab thickness increases. An investigation of these aspects is the subject of the present letter.

2. RAY-OPTIC VS. LEAKY–WAVE MODELS

The frequency-dependent relative permittivity of a lossless plasma medium is

$$\varepsilon_r(f) = 1 - \frac{f_p^2}{f^2} \qquad (1)$$

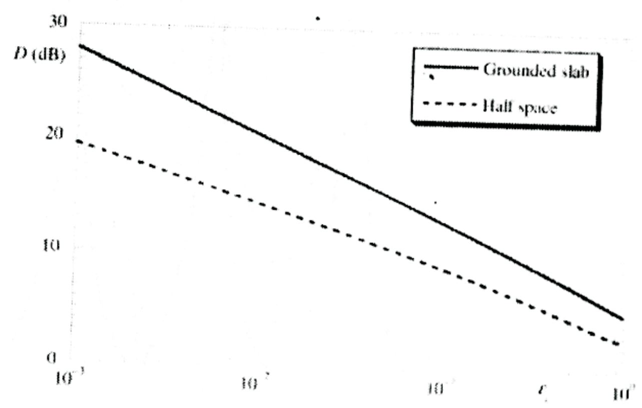


Figure 3 Directivity at broadside (in dB) as a function of the relative permittivity for an optimized grounded slab [Fig. 1(a), with h = hopt) and for a half-space Fig. 1(b)] In the two cases the same distance h,=hopt/2 of the electric line source from the air–metamaterial interface is assumed. In both cases the metamaterial is lossless.

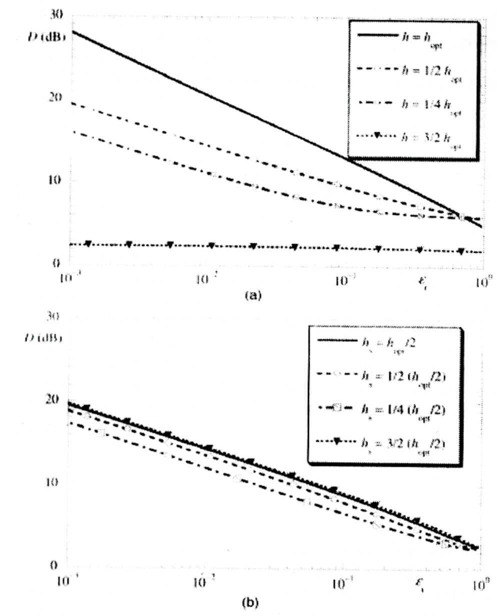


Figure 4 Directivity at broadside (in dB) as a function of the relative permittivity for (a) a lossless grounded slab with various thickness h and h_s=h/2, and (b) a lossless half—space with the same distances of the source from the air metamaterial interface as in (a)

where fp is the plasma frequency. This equation models well the effective relative permittivity of a wire medium when the electric field is parallel to the wires [8 —12]. For f > f_p (the "transparent" region) the effective relative permittivity is always positive and smaller than unity. Therefore, the rays emitted by a source placed inside a slab operating inside the transparent band will he retracted at the interface with a denser medium (e.g.. air) with transmitted angles smaller than the critical angle $0_c = \sin^{-1}\sqrt{\varepsilon_r}$;
this suggests a possible broadside directivity enhancement with respect to ordinary slabs. In Ref. 5 it was pointed out that, although very intuitive, this explanation captures only one aspect of the involved phenomenon mid that a complete picture of the high-directivity effect can be obtained by considering the excited leaky-wave field (LWF) that propagates away from the source along the interface In particular, the LWF can be thought as a wave field that consists of waves bouncing between the ground place lane and the top interface these waves add constructively when the slab has an optimum thickness to give maximum radiation at broadside, and such a constructive interference gives rise to an extremely directive broadside beam of radiation, A qualitative description of the two versions of the high-directivity phenomenon is sketched in Figure 2.

However, it still remains unclear busy much of the overall directivity enhancement is actually due to the refraction at the top interface [which is the “ray-optic” effect in Fig. 2(a)] and how much of it is due to the constructive interaction between the two interfaces, which constitutes the leaky mode in Figure 2(b). Along the interface the LWF has the form

$$E_y^{LW}(x) = A_{LW} e^{-jkLW|x|}, \tag{2}$$

where $k_{LW} = \beta - j\alpha$ [5]. Fur the plasma half—space there are no leaky waves [5] and the enhanced directivity is solely due to a ray–optic effect, In an effort to explore the importance of the leaky

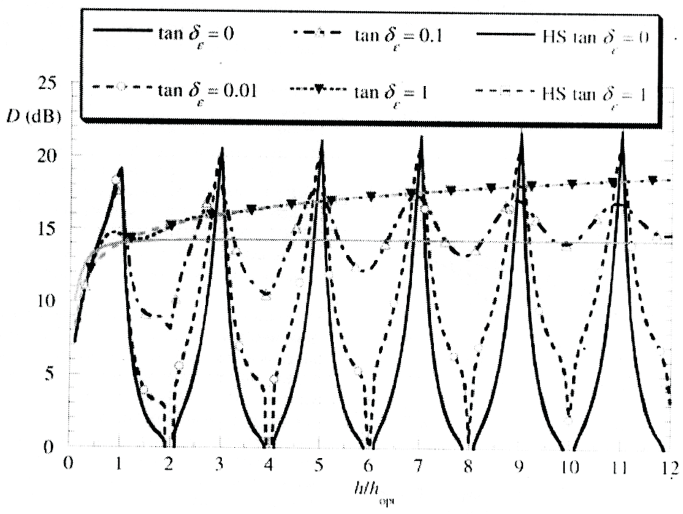


Figure 5 Directivity at broadside [in dB) as a function of the thickness h for a lossless grounded stab with hs = h/2, for different values of the loss tangent Also shown are results for lossless and lossy half—spaces, where the distance of the source from the interface is the same as for the stab. The optimum thickness H_{opt}= 59.2mm is chosen from Eq. (3) when f = 1.008% (this corresponds toε_r= 0.0158)

wave versus ray optics, in Figures 3 and 4 we have calculated the directivities for two eases, a grounded plasma slab and a plasma half-space, with no losses.

In the 2D case of line-source excitation, the broadside directivity D is defined as

$$D = \frac{2\pi P(0)}{\int_{-\pi/2}^{\pi/2} p(\theta)\, d\theta}, \tag{3}$$

where P(θ) is tire radiated power density (power per unit angle). A comparison is made between the directivity of a tune source in the middle of a plasma stab of thickness h and a line source at a distance hs from the interface of a plasma half–space. To get a fair comparison, the distances from the line source to the top interface are the same in both eases so that $h_s = h/2$. Moreover, the slab thickness is chosen from the optimum condition that maximizes tine broadside power density (and gives, approximately, the maximum (directivity) [5] as

$$h - h_{opt} = \frac{\pi}{k_o\sqrt{\varepsilon_r}} = \frac{\lambda_r}{2}, \qquad (4)$$

where k_0 and λ_0 are the wavenumber and wavelength in free space and $\lambda_E, = \lambda_0/\sqrt{\varepsilon_r}$ is the wavelength inside the plasma slab. (With this optimum slab thickness, locating the source in the middle of the stab their maximizes the broadside power density.) More generally, the power density at broadside is maximized when the slab thickness is chosen as h = nhopt, for a = 1,3,5,...., For even values of n the power density at broadside will be zero when the source is in the middle of the slab [5]; however, for other source locations ($h_s \neq h/2$) the values n = 2,4,6,.... also produce a maximum power at broadside. The results are reported in Figure 3, where the directivity is compared between the slab and half-space configurations; in both eases the line source is at a distance $h_s = h_{opt}/2$ from the top interface. The directivity of the half-space increases as the permittivity r, decreases, and this is due to the geometrical ray-optic effect that occurs at the top interface [Fig. 2(a)] - The directivity of the slab is significantly larger. however, and this is because of the constructive interference of multiple ray bounces within the stab. which constitutes the leaky mode. In particular, for smaller permittivities, the leaky-wave effect gives roughly an order of magnitude increase (more than 10 dB) in directivity compared with what the ray-optic effect alone produces. For the slab problem there is still a ray-optic effect, but the leaky-wave effect is dominant. For stab thicknesses that are not optimal, the leaky wave may become less important and this is explored below.

The use of suboptimal thicknesses (i.e., $h < h_{opt}$ reduces the value of the directivity significantly as can be seen in Figure 4(a), where different values of the stab thickness h are considered; the same occurs for slabs thicker than the optimum one (i.e., $h > h_{opt}$). (The source is still at a distance $h_s = h/2$ from the interface in alt cases.) In Figure 4(b) the corresponding changes in the directivity for the half-space configuration are reported for the same values of $h_s = 2h$ used inn Figure 4(a). It is observed that the directivity monotonically increases as h (and thus hs) increases for he half-space. but the effect of varying h on the directivity is much less compared to the effect observed in the slab problem. This is consistent with the physical mechanisms involved, In ray optics, an increase in hs simply results in a larger effective aperture due to a geometrical lensing effect. For the slab structure, the leaky mode corresponds to a resonant constructive interference in the multiple wave bounces between the interface and the ground plane, and is thus critically dependent on the stab thickness h, Moreover, a significant difference can he observed for slabs that are thicker than the optimum one; in this ease, the broadside directivity markedly decreases [Fig. 4(a)]. This rapid decrease in the broadside directivity as the slab thickness increases beyond the optimum thickness is due to the tact that the highly directive leaky-wave beam scans away from broadside towards the critical angle θ_c, as already observed in Ref. 5.

To get more information about the dependence of the directivity on the stab thickness. Figure 5 shows D as a function of the ratio h/h_{ops} (with the source placed at $h_s = h/2$) for different values of the loss tangent ; the optimal thickness hopt is chosen from Eq. (3) when $f = 1.008f_p$, this corresponds to $\varepsilon_r = 0.0158$). It can be seen that a "periodic" type of effect is present, and the broadside directivity has maxima corresponding to a odd multiple of the optimal thickness (each maximum corresponds to the optimal excitation of a successively higher-order leaky wave that radiates at broadside). The LWF is dominant for stab thicknesses close to the periodic optimal values h = nhopt (nodd), thus giving rise to the high-directivity effect at broadside. It is less important for suboptimal stab thicknesses. This is verified in Figure 6(a), which shows that for suboptimal thicknesses h < hopt the LWF decays much faster white the space-wave field

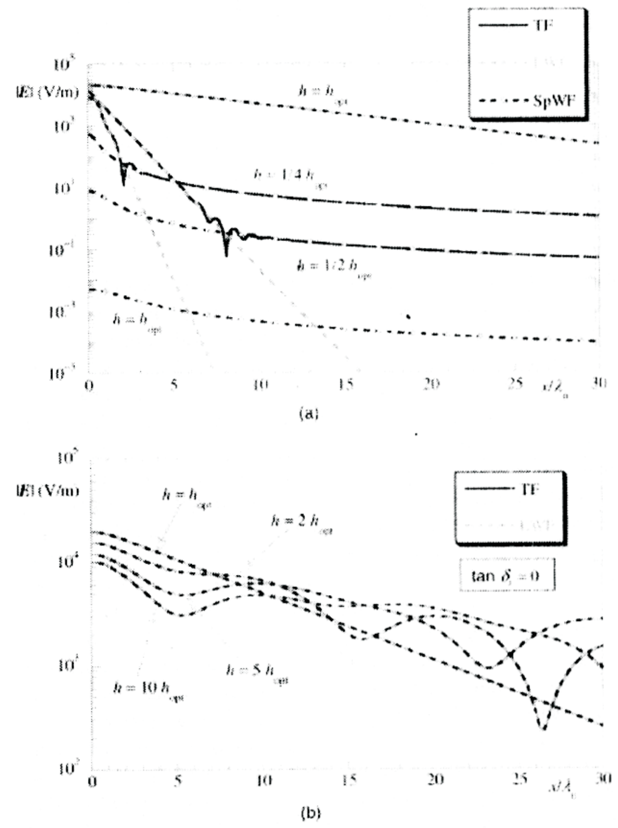


Figure 6 Amplitude of tie electric field at the air–slab interface as a function of the normalized distance from the source x/λ_0 for different values of the slab thickness, for a lossless slab : (a) $h_s = h/2$ for $h <$ hopt ; (b) hs = $h_{opt}/2$ for $h > h_{opt}$ TF : total field; LWF: leaky-wave field; sp WF; space-wave field parameters; f_p= 20 GHz, f= 1.008fp GHz, and h_{opt} = 59.2 mm.

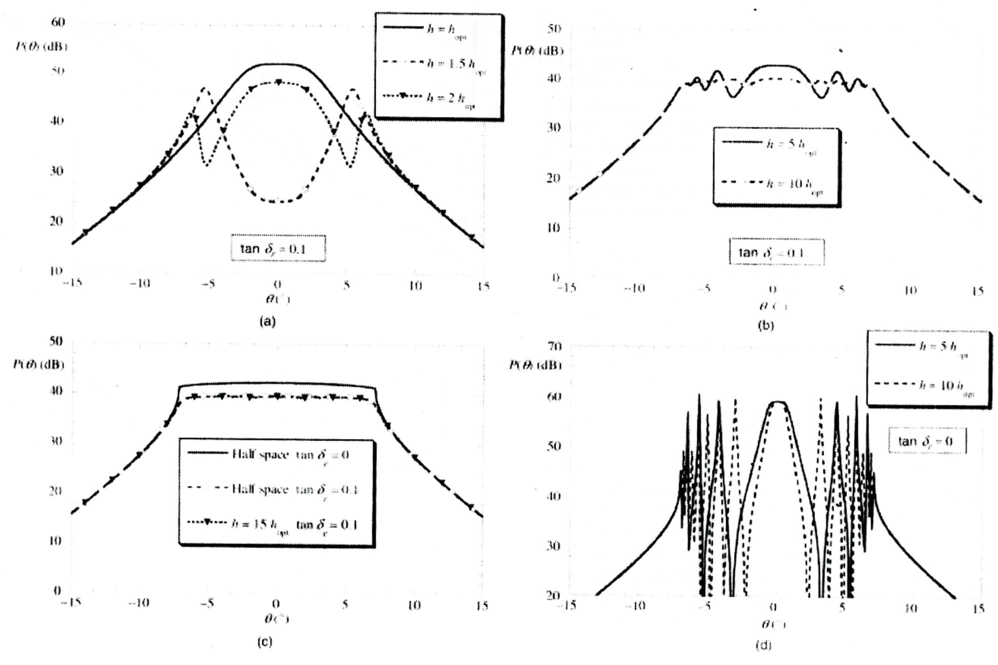


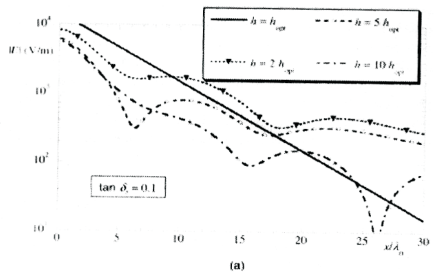
Figure 7 (a and b) Radiation patterns (in dB) for a lossy grounded slab (with parameters as in Fig. 6 with δ_ε = 0.1 and different values of the slab thickness, when the source is placed at a fixed distance hs = $h_{opt}/2$ from the slab—air interface. (c) Comparison between the radiation patterns of a lossy grounded slab its in (a) and (b) with h = 15 h_{op}t and corresponding lossless and lossy half–spare problems (both structures have the source placed at a fixed distance hs = $h_{opt}/2$ from the interface). (d) Same as in (b) but with tan δε= 0

(SpWF) becomes stronger. (The SpWF is defined as the residual field that is left over when the LWF is subtracted from the total field (TF). Far away from the source, this field decays asymptotically as $|x|^{-3/2}$ [14.Chap.5] By adding loss, the periodic fluctuations Figure 5 decrease, since the multiple bounces within the slab that constitute the LWF are more attenuated as the slab thickness increases. In the lossy case the directivity should approach that of the half-space as the thickness increases, as is clearly visible in the tan δε= 1 case of Figure 5. Also the curve tan δε=0.1 is beginning to exhibit this behavior (although convergence to a limiting value occurs for thicknesses off the scale of the plot).

To determine how the use of nonoptimal slab thicknesses affects the dominant role of the LWF, a comparison between the exact total field, the LWF, and the SpWF is presented in Figure 6. In particular, the amplitude of the corresponding electric fields at the air—slab interface is reported as a function of the normalized distance ft-urn the source for it structure as in Figure 1 with fp

20GHz. at the frequency f = 1.008fp, for which ε_r =0.0158 and 59.2 mm mm. (This structure is the same as that considered in Ref. 5, where the calculation of the constituents of the electric held has also been explained.) It can be seen that, as expected, for h = h_{opt} the LWF is completely superimposed to the TF, thus revealing its dominant character over a large portion of the interface, For slab thicknesses smaller than hopt [Fig, 6(a)] the contribution of the SpWF becomes more important as the slab thickness becomes smaller than h_{opt}/, For slab thicknesses larger than hopt [Fig. 6(b)] the TF is still superimposed to the LWF, which is now oscillating because of the interference between all the leaky waves that have been excited. In particular, as n increases in the formula h = nh_{opt} an increasingly higher–order leaky wave is responsible for the directive beam at broadside, while the lower–order leaky Waves are still present in increasing numbers.

In Figure 7, it can be observed how the far—field radiation pattern of a line source inside a lossy grounded plasma slab (with parameters as in Fig. 6) evolves into the one produced by the same source inside the corresponding lossy plasma half-space. The lass tangent is tan δε =0.1 Different thicknesses h > h_{opt} of the slab are considered, when the source is placed at a distance hk = hopt/2 from the interlace. In Figure 7(a) it can be seen that for the optimum in thickness (h= h_{opt}) the beam points exactly at broadside by increasing the slab thickness to h=15 h_{opt}/ the beam scans from broadside towards the critical angle ($\theta_c 7.1^0$). By further increasing the slab thickness to It 2 h_{opt} the beam has nearly reached the critical angle, while a higher-order leaky wave has begun to radiate at broadside. As the slab thickness increases still further [Fig. 7(b)] additional peaks (due to higher-order leaky waves) emerge, although the amplitude of the pattern oscillation decreases due to the loss, Eventually, for very thick slabs (h =10 h_{opt}) the pattern oscillation dies out and the pattern begins to become smooth, For h = 15 h_{opt} [Fig. 7(c)] the pattern has become quite smooth, and it is seen front Figure 7(c) that it is almost coincident with the pattern of the line source inside the corresponding lossy hall-space (keeping the slime distance of the source



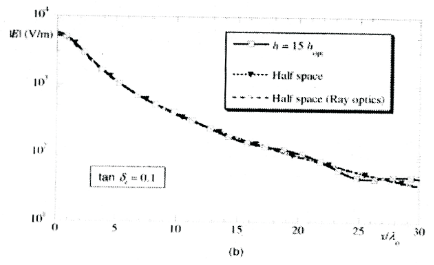


Figure 8 Amplitude of the electric field at the slab—air interlace: (a) as a function of the normalized distance from the source x/λ_0 for the lossy grounded slab of Figures 7(a) and 7(b). for different values of the slab thickness h, with hs= $h_{opt}/2$ (b) Comparison of this held with that existing at the interface in the corresponding half-space problem (having the same distance hs= $h_{opt}/2$ between the source and the interface). For the half-space problem, the held at the interface that is predicted by ray optics is also shown for comparison from the interlace. hs= $h_{opt}/2$). Figure 7(c) also shows that the pattern of the source inside the lossy half-space is not that different from the corresponding pattern for the lossless half-space, which is to be expected since the loss is not that large.

In Figure 7(d) the same radiation patterns are shown, as in Figure 7(b). but for a lossless slab. It is seen that in the absence of loss, the pattern for a thick slab becomes wildly oscillating with many sharp peaks, due to the higher-order leaky waves. Each excited leaky wave produces a peak that is confined to the angular region $-\theta c < \theta < \theta c$. Increasing the slab thickness increases the number of peaks in the region $-\theta c < \theta < \theta c$. The effect of loss smoothes out the radiation from the sum of leaky waves and produces the "plateau" pattern in Figure 7(c).

Figure 7 thus shows how the pattern changes from a leaky–wave type of pattern that is rapidly oscillating to a "lens" type of pattern (which is almost constant out to the critical angle, and almost zero beyond), as the slab thickness increases, provided there is some loss. In the completely lossless case, the slab pattern never approaches that of the half–space, and becomes increasingly oscillatory as the thickness increases, due to the higher-order leaky waves,

Figure 8 shows the amplitude of the electric field at the air–plasma interface for the same structures considered in Figure 7, as a function of the normalized distance from the source for the same values of h considered in Figure 7. When h= h_{opt}, Figure 8(a) shows that the interface held in the lossy grounded slab problem is almost entirely due to the dominant leaky wave. and is thus exponentially decaying (a straight line on the log scale) The field is significantly different from the total field of the lossy half–space problem. However, for larger values of h, the lossy grounded-slab and the lossy half–space interface fields are more alike. For h = 15hopt Figure 8(b) shows that the aperture fields of the lossy slab and half-space have become essentially the same. This is consistent with the behaviour of the radiation patterns observed mm Figure 7(c).

The field on the half–space interface can be approximated quite accurately by using a ray–optic formulation, as shown by the comparison between the exact interface field and the ray-optic approximation, included in Figure 8(b). The latter is evaluated as the incident field of the line source (with the Hankel function approximated by its first—order asymptotic expansion) multiplied by the Fresnel plane-wave transmission coefficient at the interface.

It is very reasonable that the ray-optic field accurately describes the exact interface field when the source distance hs, is large and the distance x from the source along the interface is not too large compared with hs. However, it is less clear how well the ray-optic result should agree with the exact interface held for extreme distances x. An asymptotic analysis of the half—space problem (omitted here) shows that the interlace field can be expressed as the sum of two terms, arising front steepest-descent integrations from the branch points at

$$k_1 = k_0 \sqrt{\varepsilon} = 2\pi / \lambda_r$$

and k_0 in the complex k_s plane [14, p. 321]. (We are assuming x h_s, so that the steepest-descent paths are vertical lines starting from the two branch points.) Both fields decay asymptotically along the interface as |x|–3/3. An asymptotic evaluation of the wave arising from the k_0 branch point under the assumption that x hs yield a result that mathematically approaches the field along the interface predicted by ray optics, provided the source, distance hs, becomes" large. The wave arising from the k_0 branch point is one that is commonly referred to as a "lateral wave" [14, p. 308]. An asymptotic evaluation of this wave shows that the amplitude of the corresponding interface field is exponentially small as the source distance hs increases. Hence, as the source height increases, the lateral–wave field on the interface is negligible, and the correct asymptotic evaluation of the interface field conicides with the ray–optic result.

3. CONCLUSIONS

A low–permittivity grounded metamaterial slab with a line source inside can be used to obtain a highly directive beam at broadside. When the structure is properly optimized (h= h_{opt}). the directive broadside radiation is mainly due to a single leaky wave that is excited by the source. However, whets h < hopt the directivity decreases and the role of the leaky wave becomes less important. For larger slab thicknesses (h > h_{opt}) multiple leaky waves are always important when the slab is lossless, and produce multiple directive beams that are confined to an angular region between broadside and the critical angle. This results in an overall pattern that is wildly oscillating, For a slab that has some loss, the oscillations die out and the pattern stabilizes as the slab thickness increases. The pattern and directivity then approach that of the corresponding lossy hall space.

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