2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

Study of the Efficiency of Half-Width Substrate Integrated Waveguide Leaky-Wave Antennas in FR4

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Abstract

A study of the efficiency of a planar leaky-wave antenna in half-width substrate integrated waveguide technology with low-cost and lossy material is presented. Theoretical results show the limitations in the performance of leaky-wave antennas using low-cost substrates in terms of radiation, dissipation, spillover and aperture efficiencies. It is shown that, for a given lossy substrate, the maximum achievable radiation efficiency is related to the dissipation rate. Also, a maximum useful antenna length is reported for a given substrate.

1. Introduction

Planar leaky-wave antennas (PLWAs) combine the advantages of the planar technology, i.e. low cost, integrability and low profile, with those of leaky-wave antennas (namely: high directivity, inherent frequency beam scanning, and simple feeding characteristic [1]). For this reason, a lot of interest has arisen in the study and development of PLWAs in different technologies, such as microstrip [2] or coplanar [3]. More recently, substrate integrated waveguide (SIW) [4, 5] and half-width SIW (HWSIW) [6] have been proposed as novel substrate-based LWAs. However, in all these works low-loss materials are used for the designs in order to reduce the dissipation in the substrate. Cheap FR4 substrate has been extensively used for low-cost microstrip patch antennas [7]-[12], but to the authors' knowledge this well-known substrate has never been applied to the design of LWAs. Probably this is due to the high dielectric loss constant (typically in the order of $tan\delta$=0.01), which drastically reduces the associated directivity and gain in the case of LWAs. In this work, we study the effect of the losses of a cheap material like FR4 in the performance of a PLWA in terms of the radiation and aperture efficiencies, and we quantitatively determine how much they can be exploited.

In section 2, a brief theoretical explanation of the efficiencies of a planar leaky-wave antenna (LWA) in lossy materials is reported. Practical results are presented in section 3 for the particular case of a HWSIW LWA, like the one presented in [5]. Finally, section 4 presents the conclusion of this work, which stablishes the limitations and maximum efficiency limits of high-loss PLWA designs.

2. Efficiency of PLWAs in lossy materials

In LWAs, the power injected in the structure P_0 can be divided in different terms, as shown in the next expression:

$$P_0 = P_{RAD} + P_{DISS} + P_{SpillOver} \qquad (1).$$

Where P_{RAD} is the radiated power, P_{DISS} is the power dissipated in the dielectric which sustains the structure and $P_{SpillOver}$ stands as the power reaching the end of the antenna.

Given this breakdown, it is possible to define some efficiencies and factors as the relation between each term of power in (1) and the injected power:

$$\begin{aligned} 1 &= \frac{P_{RAD}}{P_0} + \frac{P_{DISS}}{P_0} + \frac{P_{SpillOver}}{P_0} = \\ &= \eta_{RAD} + k_{DISS} + k_{SpillOver} \end{aligned} \qquad (2).$$

In (2), η_{RAD} is the radiation efficiency and relates the radiated power with the injected power. This radiation efficiency will define how well the antenna is taking advantage of the feeding power. Since the goal is to radiate as much power as possible (under some specifications), when designing a LWA a high η_{RAD} is desired. The dissipation factor k_{DISS} relates the power dissipated in the dielectric and the injected power. A high value of k_{DISS} means that there is a lot of power being dissipated in the dielectric and, hence, a high waste of power. To keep the definition of the efficiency with a positive meaning, the dissipation efficiency η_{DISS} is then written as follows:

$$\eta_{DISS} = 1 - k_{DISS} \qquad (3).$$

Another important efficiency to define is the spillover. The spillover factor $k_{Spillover}$ relates the power that reaches the output port of the antenna (see Fig.1) with the injected power. This power is usually absorbed by a matched load, and therefore it is neither radiated nor dissipated in the dielectric. The same way as with the dissipation factor, a high value of $k_{SpillOver}$ means that a lot of energy is reaching the end of the antenna and it is wasted, so the definition of the spillover efficiency is the following:

$$\eta_{Spillover} = 1 - k_{Spillover} \quad (4).$$

On the other hand, an antenna aperture efficiency can be defined to relate its directivity D with the maximum possible directivity D_{max} which is obtained for the ideal case of a uniform amplitude, linear phase aperture illumination:

$$\eta_{AP} = \frac{D}{D_{max}} \quad (5).$$

The final gain of an antenna will depend on the aperture and radiation efficiencies by the next expression [13]:

$$G = D * \eta_{RAD} = D_{max} * \eta_{AP} * \eta_{RAD} \quad (6).$$

2.1 Obtaining of efficiencies from the radiation and dissipation rates

All the terms in (2) can be obtained through the power carried by a leaky mode at any point along the antenna longitudinal direction y:

$$P(y) = P_0 * e^{-2*\alpha_T*y} \quad (7).$$

Where P_0 is the injected power and $\alpha_T = \alpha_{RAD} + \alpha_{DISS}$ is the leaky-mode total attenuation rate, including radiation and dissipation rates.

Using (7) and its derivative, the next expressions for the efficiencies can be obtained:

$$\eta_{RAD} = \frac{\alpha_{RAD}}{\alpha_T}(1 - e^{-2*\alpha_T*L_A}) \quad (8).$$

$$\eta_{DISS} = 1 - k_{DISS} = \\ = 1 - \frac{\alpha_{DISS}}{\alpha_T}(1 - e^{-2*\alpha_T*L_A}) \quad (9).$$

$$\eta_{Spillover} = 1 - k_{Spillover} = \\ = 1 - e^{-2*\alpha_T*L_A} \quad (10).$$

Where L_A is the antenna length. More details on the demonstration of (8), (9) and (10) will be given in the presentation.

It can be seen from (8) that the radiation efficiency depends on the relation between the radiation rate and the total attenuation rate, which includes the dissipation rate as well. For a given radiation and attenuation rates, a maximum radiation efficiency can be defined for sufficiently long antennas:

$$\eta_{RAD,max} = \eta_{DISS,min} = \\ = \frac{\alpha_{RAD}}{\alpha_{RAD} + \alpha_{DISS}} \quad (11).$$

In this case, the spillover efficiency will be 100%, (indicating that no power reaches the far end of the antenna), and both radiation and dissipation efficiencies will have the same value given by (11). If the antenna is even longer, these efficiencies will not improve, meaning that a portion of the antenna will be unused.

The only efficiency left to define is the aperture efficiency. In this case, the directivity of a LWA must be defined and compared to the one of a uniformly illuminated aperture with the same length. With this purpose, the directivity of a LWA is obtained through the assumption that it behaves as a magnetic line source. In this case, it can be written as follows [13]:

$$D(\theta_0) = \frac{2 * |SF(\theta_0)|^2}{\int_{-\pi/2}^{\pi/2} |SF(\theta)|^2 \cos(\theta) d\theta} \quad (12).$$

Where θ is the elevation angle from the broadside direction and $SF(\theta)$ is the so called *source factor*, defined as:

$$SF(\theta) = \\ = \int_0^{L_A} M(y) e^{j[k_0*y*cos(90-\theta)+\varphi(y)]} dy \quad (13).$$

In (13), $M(y)$ and $\varphi(y)$ are the amplitude and the phase of the illumination of the antenna, respectively, and they depend on the real and imaginary parts of the leaky complex longitudinal wave number $k_y = \beta_y - j\alpha_y$:

$$M(y) \sim \alpha_{RAD} * e^{-\alpha_y*y} \quad (14).$$

$$\varphi(y) = -\beta_y * y \quad (15)$$

In the case of the uniformly illuminated aperture, the amplitude $M(y)$ does not vary along the aperture.

3. Results for a HWSIW LWA

Previous theoretical results are valid to any type of 1D source unidirectional LWA. In this section, we particularize for a practical HWSIW LWA. As it will be seen, some tradeoffs must be taken into account to achieve the best design for a certain application. The structure of a HWSIW LWA is shown in Fig. 1. All the graphs in this section are obtained for a radiation angle of $\theta_{RAD} = 30$º and an operating frequency $f_0 = 2.45$ GHz. The material chosen for the substrate is FR4 with $\varepsilon_r = 4.48$, $tg\delta = 0.01$ and thickness $H = 1\, mm$.

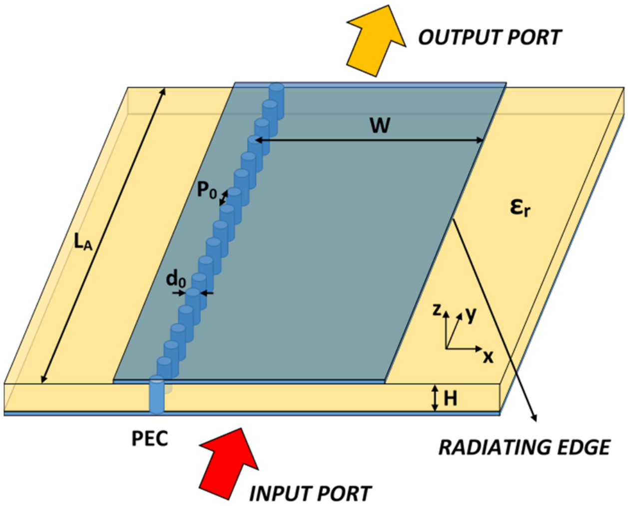

Figure 1. Structure of a HWSIW LWA.

In Fig. 2, the variation of η_{RAD}, η_{DISS} and $\eta_{Spillover}$ with the antenna length L_A is represented. It can be seen how as the antenna is longer, the spillover efficiency increases, meaning that less power reaches the end of the antenna. In our case, maximum $\eta_{Spillover} = 1$ is obtained for $L_A = 5\lambda_0$. For longer antennas, the further sections of the antenna ($y > 5\lambda_0$) will not be illuminated, since no more propagating power is left inside the leaky waveguide. The radiation efficiency η_{RAD} also has an increasing behavior as the antenna becomes longer, and it stabilizes at the same length $L_A = 5\lambda_0$ (since no more power can be radiated far from this length). This upper limit is $\eta_{RAD,max}$ (11), which in our case is 50%. Finally, the dissipation efficiency η_{DISS} has a decreasing behavior: more power is dissipated in the supporting dielectric as the antenna becomes longer. This efficiency tends to a minimum value $\eta_{DISS,min}$ for the aforementioned maximum length $L_A = 5\lambda_0$ which, as indicated in (11), coincide with the maximum radiation efficiency (50% in our case). Therefore, we can establish a maximum useful antenna length $L_A = 5\lambda_0$. Using higher values is a waste of physical length which is not used as effective radiating length.

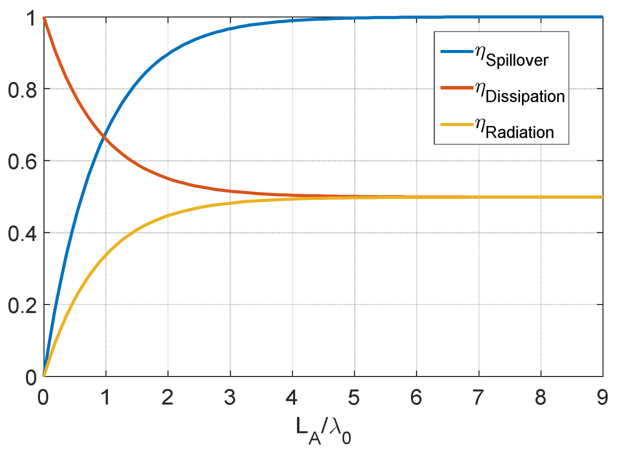

Figure 2. Radiation, dissipation and spillover efficiencies as a function of the antenna length L_A for a substrate thickness $H = 1\,mm$.

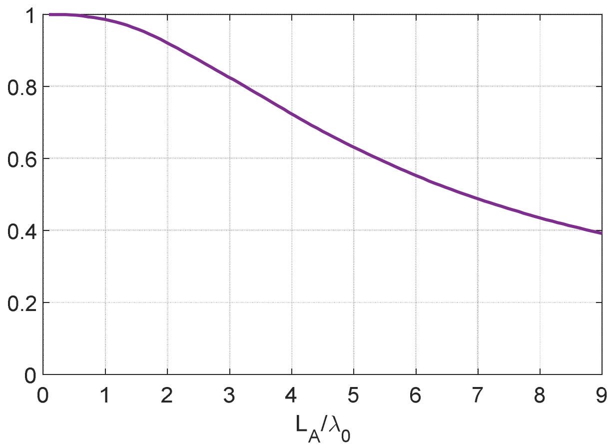

Figure 3. Aperture efficiency as a function of the antenna length L_A for a substrate thickness $H = 1\,mm$.

On the other hand, the aperture efficiency η_{AP} decays as the LWA becomes longer, as it is shown in Fig. 3. This is due to the inherent exponentially-decaying aperture illumination of a non-tapered LWA. As commented, this makes the last sections of the antenna to be poorly illuminated if compared to the ideal uniform illumination case.

Once we have characterized the effect of the antenna length in the different LWA efficiencies, the curve of radiation efficiency in Fig. 2 and the one of the aperture efficiency in Fig. 3 can be used to estimate the gain according to (6). Particularly, the product of both efficiencies $\eta_{AP} * \eta_{RAD}$ determines the overall LWA efficiency (the ratio between the obtained gain and the maximum ideal directivity). This curve has an optimum point, due to the complementary dependence with the antenna length of the radiation efficiency (which increases with L_A) and the aperture efficiency (which decreases with L_A), as shown in Fig.4a.

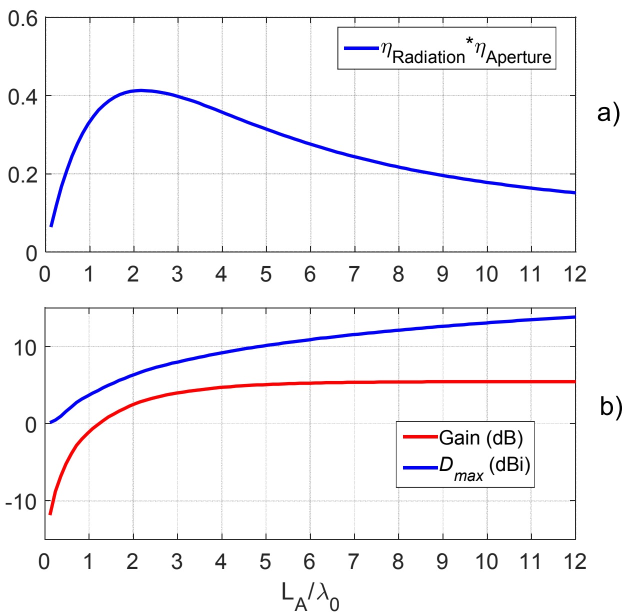

Figure 4. a) Overall LWA efficiency $\eta_{RAD} * \eta_{AP}$ and b) LWA maximum directivity and obained gain.

For the studied case we can obtain a maximum 41.3% efficiency for an antenna length of $L_A = 2.16\lambda_0$. For this length, the maximum directivity is D_{max}=6.7dBi, and thus the obtained gain is G=2.8dB. As the LWA becomes longer, the maximum potential directivity of the antenna monotonously increases. However, due to the aforedescribed effects, the real gain is limited to a maximum value of G=5.4dB, which is obtained at the aforementioned maximum useful antenna length $L_A = 5\lambda_0$. Further works will be conducted to study the effect of the substrate height and the radiation angle, in order to determine the optimum design. This will allow to take the most of high-loss FR4 substrate, intended for directive frequency-scanning low-cost LWA designs.

4. Conclusion

The limitations of a PLWA made using a lossy substrate have been studied. An expression for the maximum value of the radiation efficiency is presented, showing that it is related to the radiation and dissipation rates. It has been shown that this limits the maximum useful antenna length. Also, it has been demonstrated that there is an optimum length to obtain the maximum overall antenna efficiency, which takes into account both the radiation and aperture efficiencies, and determines the antenna gain which is strongly reduced due to dissipation effects of high-loss substrate. This gain reduction needs to be taken into account when designing a PLWA for low cost applications.

7. References

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