Low-Reflection Millimeter-Wave Composite Lens

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***Abstract*-Lenses are traditionally based on dielectric materials with their shape determined by the refractive index of the material in question and the desired focal distance. A dielectric substance inevitably causes some unwanted reflections at the interfaces between the lens and the background medium due to the mismatch of wave impedances on the two sides of the lens interface. Here we employ a simple way to partly overcome this problem by using a volumetric transmission-line network as a composite lens material. A design operating in the frequency band of 77 GHz—81 GHz is presented and its functionality is verified with numerical simulations. The designed composite lens is also compared to a dielectric analogous having the same shape and refractive index.**

I. Introduction

Volumetric transmission-line networks have been successfully implemented as homogeneous, effective materials with exotic propagation properties [1],[2]. Here we employ a two-dimensional transmission-line network as a volumetric structure emulating a homogeneous magnetodielectric substance [3],[4],[5]. This medium can be used as a lens, focusing a plane wave into a point, or into a line as is done here. It is shown with numerical full-wave simulations that the proposed design exhibits a much lower level of reflections across the lens interfaces, than a conventional dielectric lens of the same shape. We use the same lens profile as in [4], but for operation in the millimeter-wave band, namely, in the frequency range from 77 GHz—81 GHz which is commonly used in automotive radar applications.

A semi-analytical model is introduced and used in the design of the lens. Although accurate analytical models exist for the transmission-line network as such (see [1]-[5]), the tapered metal layer used to couple the electromagnetic waves between the background medium and a volumetric, periodical set of transmission-line networks has so far been designed numerically. In the design of lenses this is problematic, since the whole structure needs to be simulated in order to optimize the operation of the lens. This design procedure can be greatly simplified by using a semi-analytical model. In [6], we introduced a fully analytical model of tapers connected to transmission-line networks. In this work, we modify that approach so that the transmission-line network is modeled numerically and this numerical result is combined with the analytical model of the tapers. This approach enables accurate but still very fast modeling and design of the structure dimensions, since the characteristics (wavenumber, impedance) of the network are taken into account better than in the fully analytical model of [6].

II. Profile of the Lens

The dielectric lens profile is designed with the well-established equations employed when the focal distance and refractive index of the lens material are known. In this work, one interface of the lens is planar and the other has the same profile as in [4], while the refractive index n of the medium comprising the lens is assumed to be $n=\sqrt{4.66}\approx 2.16$. A dielectric lens with this refractive index will be the reference case, with which we will compare the transmission-line based structure. The transmission-line lens has the same shape as the dielectric one, but it is comprised of stacked two-dimensional transmission-line networks. The lens profile is illustrated in Fig. 1. The analytical equation of the lens profile reads [7]

$$y^2=(n^2-1)(x-F)^2+2(n-1)F(x-F), \qquad (1)$$

where F is the focal distance. In this case, we select F=80d, where d is the period of the transmission-line network. The thickness of the lens (in the direction parallel to the optical axis) equals 10d and the width of the lens is 64d.

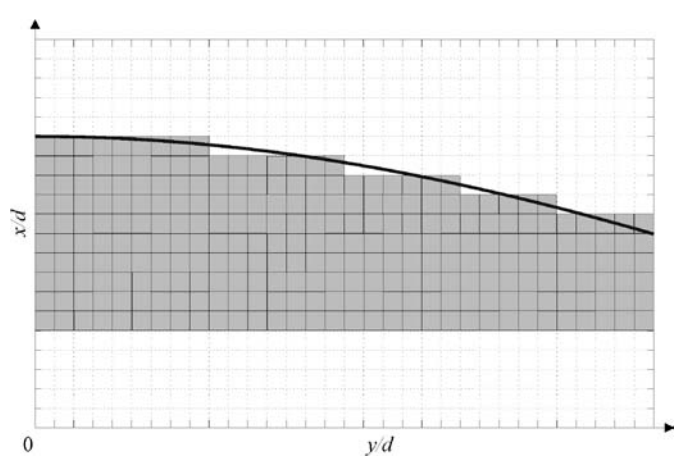


Figure 1. Lens profile. Only half of the lens is shown since the lens is symmetric with respect to the xz-plane at y=0. The grey squares illustrate unit cells of the structure. The thick black line represents the solution of (1) with F=80d.

III. Structure of the Transmission-Line Network and the Tapers

The transmission-line network is comprised of parallel strip transmission lines, such that the lines form a two-dimensional network [3],[4]. The geometry of the used transmission-line network is shown in Fig. 2. The dielectric material used in the model has the relative permittivity 2.33 and loss tangent 0.02.

Wave propagation outside the transmission lines is prohibited by metal pins having the radius r. By cascading the unit cells of Fig. 2 in the xy-plane, one can form a composite lens as illustrated in Fig. 1. Then by stacking these layers periodically along the vertical (z-) direction, one can create a volumetric structure, i.e., a volumetric composite lens. In the following we will consider the lens to be infinitely periodic in the z-direction.

The dimensions of the unit cell are chosen so that the periods (d in the xy-plane and H along the vertical direction) are small compared to the wavelength. Therefore, we choose d=0.3 mm and H=0.7 mm. The other parameters of the unit cell read w=0.05 mm, t=0.035 mm, h=0.5mm, and r=w/4. The ratio h/w is chosen to be large to obtain a reasonably high value for the impedance of the network [3,4].

The metal tapers, used to couple the electromagnetic waves between the background medium (free space) and the transmission-line network, are similar to the case studied in [6], except that here the tapers are embedded in the same dielectric material as the transmission lines. One end (the end with the height h) of each taper is connected with the transmission-line network and the other end (with the height H) connects to the background medium, i.e., free space in this case. See Fig. 3 for the geometry of the tapers.

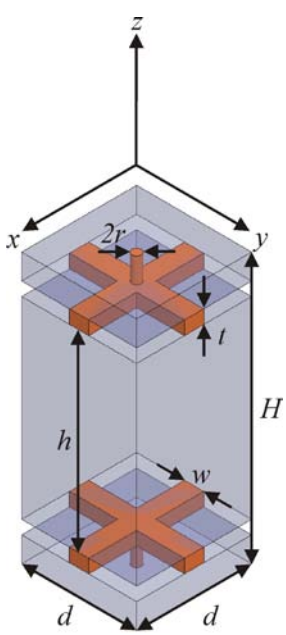


Figure 2. Unit cell of the transmission-line network. The transmission-line strips (orange) are sandwiched between dielectric layers (grey).

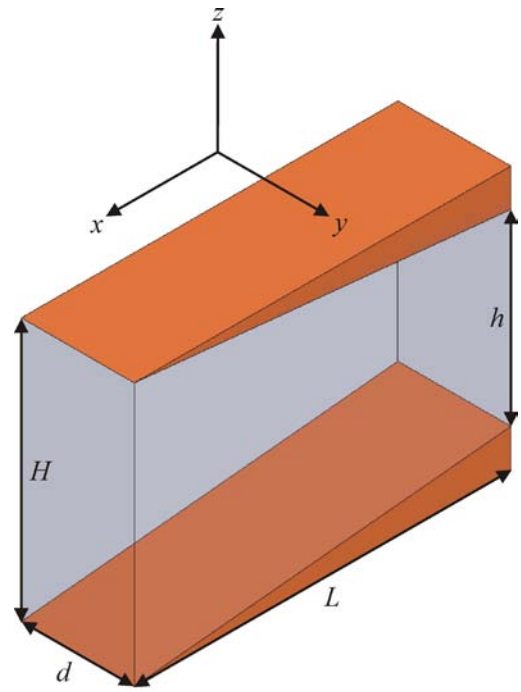


Figure 3. Taper for coupling electromagnetic waves between the background medium and a transmission-line network.

IV. Analytical Model for the Tapers

The approach to provide an analytical model for the tapered structures adopted in this work is similar to that described thoroughly in [6]. Therefore, we are simply flashing the basic features of the employed technique, avoiding detail. To manipulate the fields inside tapers, we make a "step approximation" of the inclined planes by "chopping" the internal region into a large number U of subregions, as indicated in Fig. 4. Once the parameter U is chosen high enough, the heights of two successive coplanar components are almost equal to each other. Thus, we can express the fields in each of the components in terms of the single dominant mode, which is not dependent on the z-coordinate.

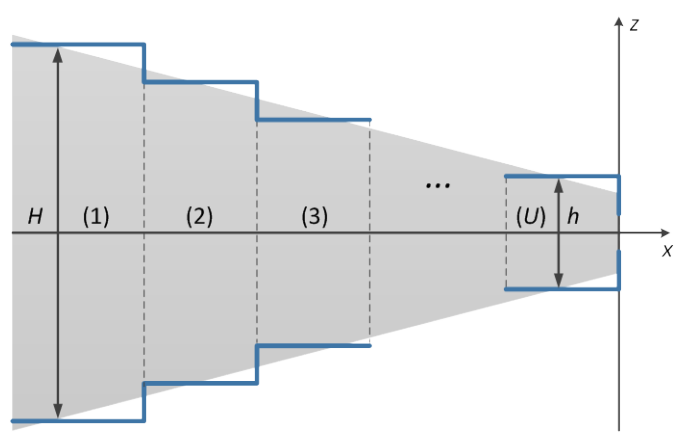


Figure 4. The taper filled with a host material is "chopped" into a large number of U subregions of equal length.

To determine the field distribution in each cell, we implement the well-known mode matching procedure. The adopted form of single-mode transmissions and reflections is not only reasonable for large U, but it renders the method more numerically effective and robust as well. The derived expressions have been evaluated and found to exhibit excellent coincidence with the corresponding numerical simulation results for arbitrary variations of the input parameters.

V. Numerical Results for Transversally Infinite Composite Slabs

The analytical model of Section IV is used in the lens design by optimizing the dimensions of the taper. In this way, we avoid the need to make extensive numerical optimization of the whole lens structure. Our approach is semi-analytical, since we combine the analytical model of the tapers with a numerical model of the unit cell of the transmission-line network. This numerical model is obtained by simulating one unit cell of the transmission-line network (see Fig. 2) and obtaining the S-parameters of the cell. Here we use the finite-element-method (FEM)-based commercial full-wave simulation software Ansys HFSS. The unit cell of Fig. 2 is modeled as a periodic structure by assigning perfect electric walls (xy-planes) and perfect magnetic walls (xz-planes) on the outer boundaries of the model. The S-parameters are calculated by assigning ports on the two yz-planes. The mode of our interest has the electric field parallel to the z-axis. These simulations were carried out with the dimensions of the unit cell given in Section III.

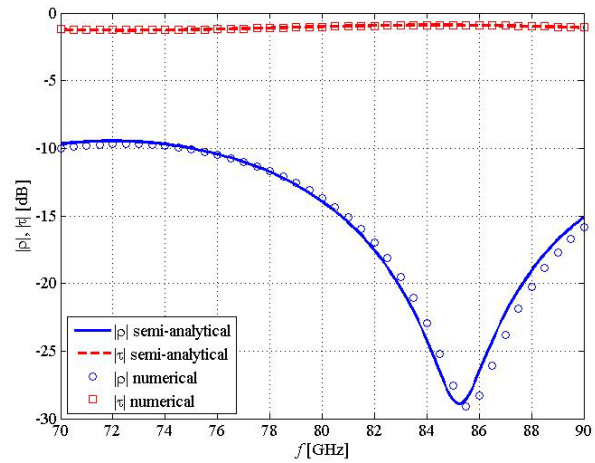
From the numerically obtained S-parameters of one unit cell, we can analytically obtain the transfer matrix (T-matrix) of this module, T_{uc}. Then, the T-matrix of N cascaded unit cells is simply $(T_{\mathrm{uc}})^N$. Now we can combine the analytical model of Section IV with this slab of N unit cells, by multiplying the various transfer matrices as follows

$$T_{\mathrm{tot}}=T_{\mathrm{taper1}}(T_{\mathrm{uc}})^N T_{\mathrm{taper2}}, \qquad (2)$$

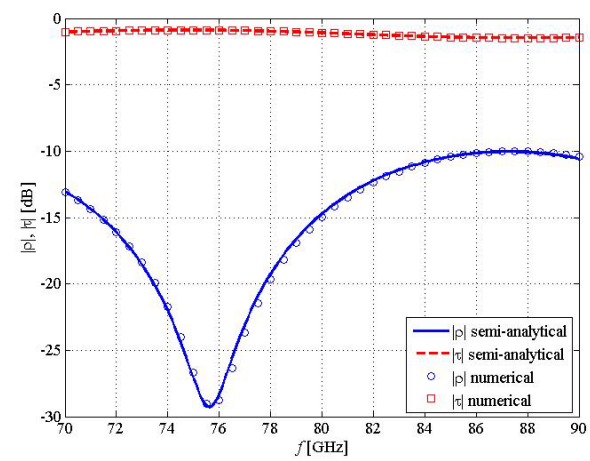
where T_{taper1} and T_{taper2} are the analytically obtained T-matrices of the two tapers on the opposite sides of the slab.

Based on (2), we find the transfer matrix for the whole slab, i.e., T_{tot}. Implicitly, we can analytically calculate the reflection (ρ) and transmission (τ) coefficients of a slab which has tapers on both sides and a transmission-line network of thickness N unit cells along the wave propagation direction (along x-axis). Note that this slab is infinitely periodic along the y-axis and the z-axis, which means that we are modeling a transversally infinite slab having the thickness $Nd+2L$.

To verify our semi-analytical model, we have used (2) to calculate the reflection and transmission coefficients for various slab thicknesses and with several lengths L. These values for a specific slab, obtained with the semi-analytical model, can then be compared to numerical results of the whole structure. In Figs. 5 and 6 we show the results for two different slabs, one with thickness N=5 and the other with thickness N=10. Two values of L are studied for both cases.



(a)



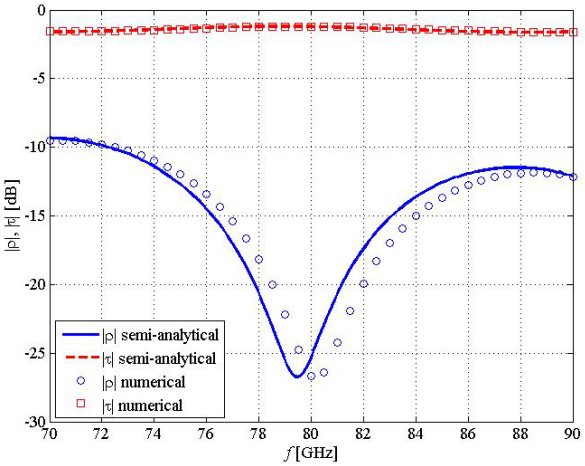
(b)

Figure 5. Reflection and transmission for a transversally infinite slab with the transmission-line network having the thickness 5d. (a) L=1 mm. (b) L=1.2 mm.

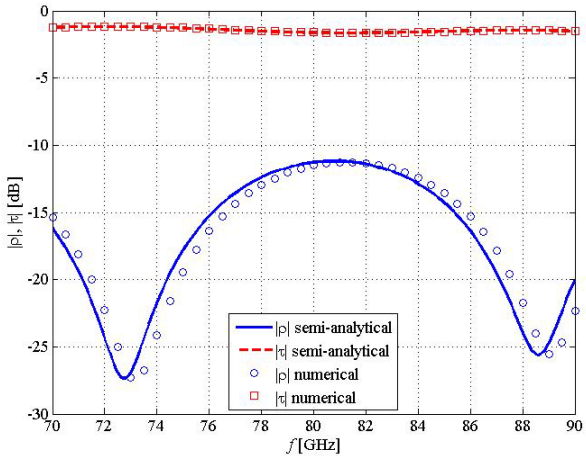
It is apparent that the semi-analytical model describes the behavior of the slabs very accurately, so that this model can be readily used in finding the optimal dimensions of the tapers.

VI. Numerical Results for a Composite Lens

The approach described in the previous section can be used to optimize the dimensions of a transmission-line composite lens, such as described in Section II. Each unit cell of this lens has the geometry presented in Fig. 2 and the dimensions given in Section III. We have used the semi-analytical model of Section V to find the optimal dimensions of the tapers, so that the reflections are minimized and transmission maximized for all slab thicknesses from 6d to 10d (see Fig. 1), in the frequency band from 77 GHz to 81 GHz. Since the dimensions of the unit cell dictate the values for h, H, and d, the only



(a)



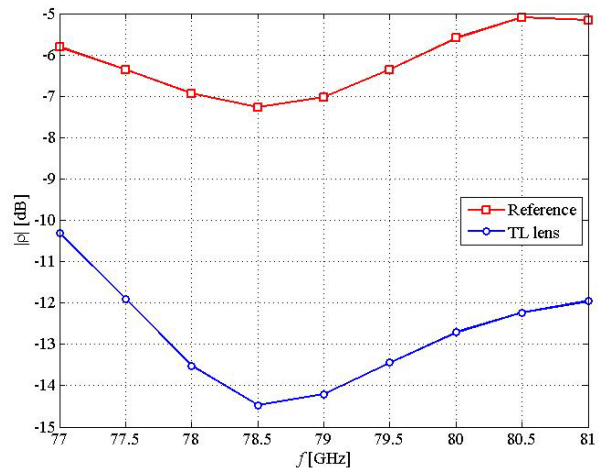
(b)

Figure 6. Reflection and transmission for a transversally infinite slab with the transmission-line network having the thickness 10*d*. (a) *L*=1 mm. (b) *L*=1.2 mm.

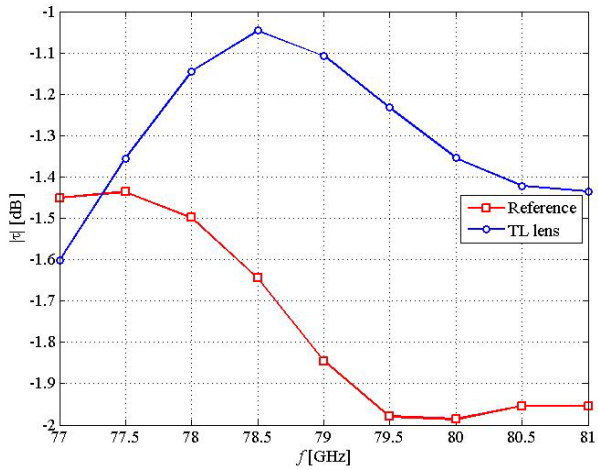
parameter left to optimize is *L*. We studied the effect of *L*, with a step of 0.1 mm, on the reflection and transmission for slabs with the aforementioned thicknesses and found that, according to the semi-analytical model, the optimal value is *L*=1 mm.

To finally verify that the actual lens operates as expected, we have made a numerical study of the whole lens by using the same unit cell dimensions as before and *L*=1 mm. The structure is modeled as being infinitely periodic along the *z*-axis, but it is finite in the *y*-direction, with the width of the lens being equal to 64*d*=19.2 mm. The results obtained with this composite lens are compared to numerical results for a dielectric lens having exactly the same profile and relative permittivity equal to 4.66 and the loss tangent of 0.02 (i.e., the same loss tangent as in the dielectric in the composite lens). These two lenses are then numerically simulated in Ansys HFSS and the resulting reflection and transmission coefficients are presented in Fig. 7. It is evident that the reflections are quite strongly mitigated in the transmission-line lens, when compared to the dielectric lens. It is also notable that the improvement in the reflection coefficient is not achieved with higher losses inside the lens, since the transmission coefficient is, in almost the whole frequency band of interest, higher in the case of the transmission-line lens.

To further demonstrate the operation of the two lenses, we show the simulated electric field distributions, at the frequency 79 GHz, in Figs. 8 and 9. In the case of the composite lens, the incident wave is well preserved on the other side of the lens due to very low level of reflections from the lens. Also inside the lens, the waveform is well preserved. As for the dielectric lens, the fields are much distorted both outside and inside the lens, due to reflections at the two lens interfaces.



(a)



(b)

Figure 7. Simulated reflection (a) and transmission (b) coefficients for a dielectric reference lens and a composite transmission-line lens.

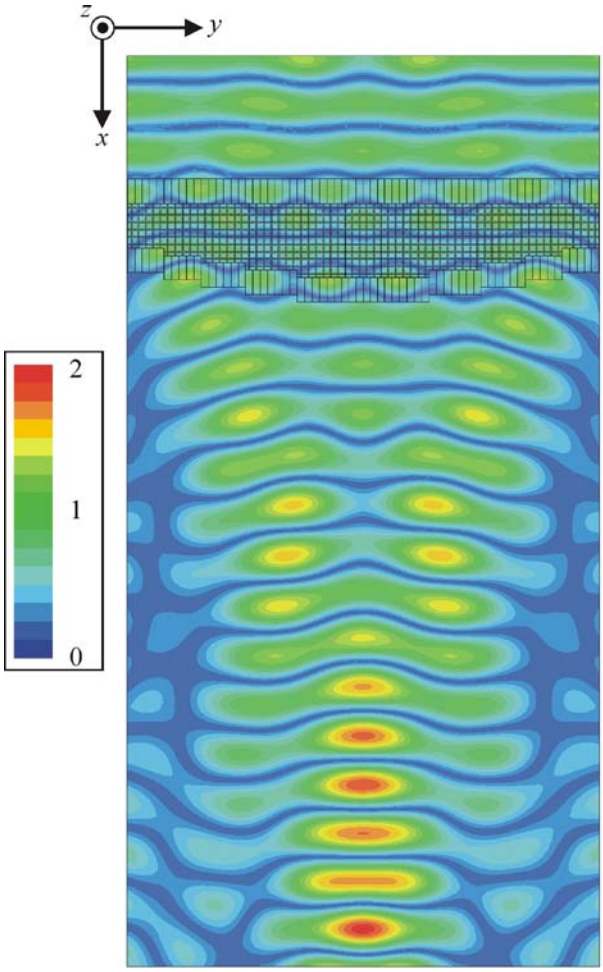


Figure 8. Snapshot of the simulated time-harmonic electric field (V/m) at the frequency of 79 GHz, in the case of the composite transmission-line lens. The incident plane wave, travelling in the +*x*-direction and having the electric field parallel to the *z*-axis, has the magnitude 1 V/m.

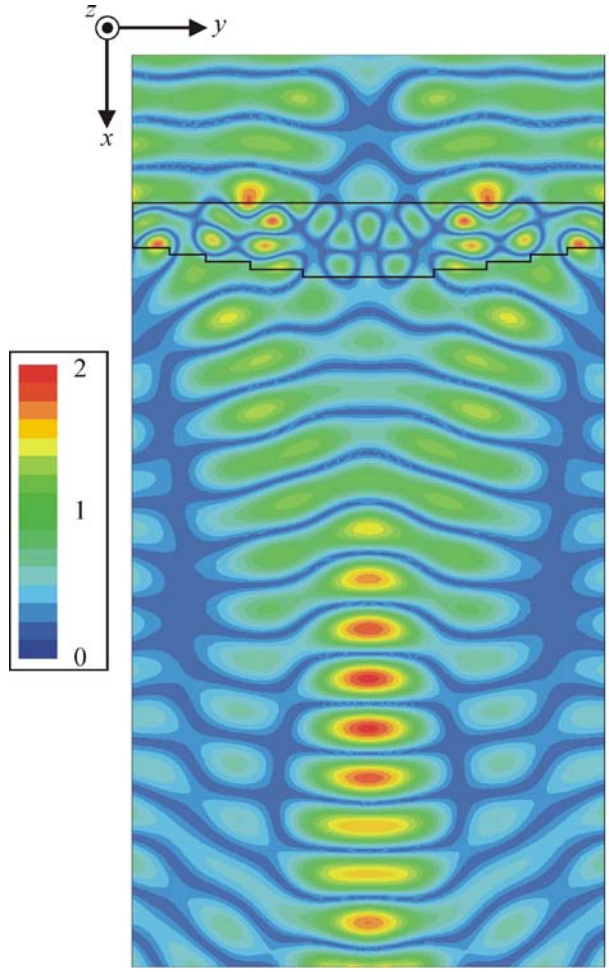


Figure 9. Snapshot of the simulated time-harmonic electric field (V/m) at the frequency of 79 GHz, in the case of the dielectric lens. The incident plane wave, travelling in the +*x*-direction and having the electric field parallel to the *z*-axis, has the magnitude 1 V/m.

VII. Conclusions

We have demonstrated a composite transmission-line lens design, the dimensions of which are optimized using a semi-analytical model. The composite lens was designed for operation at millimeter-wave frequencies, namely, in the frequency band from 77 GHz to 81 GHz. Operation of the lens is verified with numerical full-wave simulations. The operation of the designed lens is compared to a traditional dielectric lens, in terms of the levels of reflection and transmission through the lens. It has been shown that the level of reflections is much smaller in the case of the composite lens. It is also shown that the lower level of reflections is not caused by higher losses inside the composite lens.

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