Robust method to retrieve the constitutive effective parameters of metamaterials

Xudong Chen, Tomasz M. Grzegorczyk, Bae-Ian Wu, Joe Pacheco, Jr., and Jin Au Kong
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 25 February 2004; published 26 July 2004)

We propose an improved method to retrieve the effective constitutive parameters (permittivity and permeability) of a slab of metamaterial from the measurement of S parameters. Improvements over existing methods include the determination of the first boundary and the thickness of the effective slab, the selection of the correct sign of effective impedance, and a mathematical method to choose the correct branch of the real part of refractive index. The sensitivity of the effective constitutive parameters to the accuracy of the S parameters is also discussed. The method has been applied to various metamaterials and the successful retrieval results prove its effectiveness and robustness.

DOI: 10.1103/PhysRevE.70.016608 PACS number(s): 41.20.Jb, 42.25.Bs, 78.20.Ci

I. INTRODUCTION

Left-handed (LH) structures have been realized so far as metamaterials [1–3] and very quickly, researchers have been working on retrieving their effective permittivity and permeability to better characterize them [4–6]. Known methods to date [7,8] use S parameters calculated from a wave incident normally on a slab of metamaterial, from which the effective refractive index n and impedance z are first obtained. The permittivity ε and permeability μ are then directly calculated from μ=ε_n and ε=n/z.

It is also known that this retrieval process may fail in some instances, such as when the thickness of the effective slab (exhibiting bulk properties) is not accurately estimated [4] or when reflection (S_{11}) and transmission (S_{21}) data are very small in magnitude [6]. Although these issues have been addressed to some extent in previous works, we have found that the retrieved results in some cases are still unsatisfactory. In particular, the determination of the first boundary of the effective homogeneous slab, the selection of the sign of the roots when solving for the impedance z, the determination of the branch of the real part of refractive index n, and the origin of the spikes appearing in the retrieved impedance z, are many problems that deserve further investigation. The aforementioned issues are addressed in the next sections of this paper and some typical retrieval results are presented to show the robustness and effectiveness of the method. Note that the values of ε, μ, and z are relative to those in free space, thus dimensionless.

II. RETRIEVAL METHOD

A. Theoretical retrieval equations

In order to retrieve the effective permittivity and permeability of a slab of metamaterial, we need to characterize it as an effective homogeneous slab. In this case, we can retrieve the permittivity and permeability from the reflection (S_{11}) and transmission (S_{21}) data. For a plane wave incident normally on a homogeneous slab of thickness d with the origin coinciding with the first face of the slab, S_{11} is equal to the reflection coefficient, and S_{21} is related to the transmission coefficient T by S_{21}=T e^{i k_0 d}, where k_0 denotes the wave number of the incident wave in free space. The S parameters are related to refractive index n and impedance z by [7,9,10]:

S_{11} = \frac{R_{01}(1-e^{2ik_0d})}{1-R_{01}e^{2ik_0d}}, \quad (1a)
S_{21} = \frac{(1-R_{01})e^{ik_0d}}{1-R_{01}e^{2ik_0d}}, \quad (1b)

where R_{01}=z-1/z+1.

As it has been pointed out in [4,5], the refractive index n and the impedance z are obtained by inverting Eqs. (1a) and (1b), yielding

z = \pm \sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}}, \quad (2a)
e^{ik_0d} = X \pm i\sqrt{1-X^2}, \quad (2b)

where X=1/2S_{21}(1-S_{11}+S_{11}^2). Since the metamaterial under consideration is a passive medium, the signs in Eqs. (2a) and (2b) are determined by the requirement
n' \equiv 0, \quad (3a)
n'' \equiv 0, \quad (3b)

where (·)' and (·)'' denote the real part and imaginary part operators, respectively. The value of refractive index n can be determined from Eq. (2b) as

n = \frac{1}{k_0 d} [\ln (\ln |e^{ik_0d}|^2 + 2m \pi) - i \ln |e^{ik_0d}|], \quad (4)

where m is an integer related to the branch index of n'. As mentioned above, the imaginary part of n is uniquely determined, but the real part is complicated by the branches of the logarithm function.

Equations (2a) and (2b) can be directly applied in the case of a homogeneous slab for which the boundaries of the slab are well defined and the S parameters are accurately known. However, since a metamaterial itself is not homogeneous, the two apparently straightforward issues mentioned above need to be carefully addressed. First, the location of the two
These two problems are examined in detail in the following sections. The boundaries of the effective slab need to be determined, which we do here by ensuring a constant impedance for various slab thicknesses. Second, the $S$ parameters obtained from numerical computation or measurements are noisy which can cause the retrieval method to fail, especially at those frequencies where $z$ and $n$ are sensitive to small variations of $S_{11}$ and $S_{21}$. These two problems are examined in detail in the following sections.

**B. Determination of the first boundary and the thickness of the effective slab**

A homogeneous slab of material can be characterized by the fact that its impedance does not depend on its thickness. Our understanding of the physical meaning of the first effective boundary is a plane beyond which the reflected wave behaves like a plane wave for a plane wave incidence. When a plane wave is incident on a metamaterial, currents will be induced on the metals creating a scattered field. The field produced by the induced currents is not uniform: It is strongest around the metal and decay at a certain distance. The first effective boundary is located where the reflected wave behaves like a plane wave, and it has to be determined. We use $z_1$ and $z_2$ to represent the impedances of two slabs of metamaterial of different thicknesses. The reflection $S_{11}$ depends on the position of the first boundary and the transmission $S_{21}$ depends on the thickness of the slab. In addition, since the impedance $z$ is also a function of $S_{11}$ and $S_{21}$, $z$ depends on the first boundary and the thickness of the slab as well. Taking into account the above-mentioned properties, we propose a method whereby the first boundary and the thickness of the sample are determined by optimization so that $z_1$ matches $z_2$ at all frequencies.

Figure 1 illustrates the configuration of the problem for a metamaterial made of two cells in the propagation direction ($x$ direction). The geometry of the metamaterial has been taken from [11,12], in which the dimensions have been slightly modified for ease of discretization in finite-difference time-domain (FDTD) simulations. With the split-ring resonator (SRR) and rod in the center of the unit cell, the periodicity along the propagation direction is $d_0$. The first boundary of the effective homogeneous medium is located at $x_1$ below ($x_1 ≥ 0$) or above ($x_1 < 0$) the first unit-cell boundary, and the thickness of the effective medium is $2d_0 + x_2 - x_1$. The optimization model is set up to minimize the mismatch of impedances of different numbers of cells of metamaterial:

$$\min_j f(x) = \frac{1}{N_f} \sum_{f_i=1}^{N_f} \left[ \frac{|z_1(f_i, x) - z_2(f_i, x)|}{\max(|z_1(f_i, x)|, |z_2(f_i, x)|)} \right],$$

s.t.: $0.5d_0 ≤ x_1$, $x_2 ≤ 0.5d_0$, $x = (x_1, x_2)$, (5)

where $N_f$ is the total number of sample frequencies and $z_j(f_i)$ represents the impedance of slab $j = 1, 2$ at frequency $f_i$.

In the ideal case, $z_1$ matches $z_2$ for all frequencies with the objective function value equal to zero. We use the differential evolution algorithm [13] to optimize the objective function, and the optimized solution is $x_{opt} = (3.8565 \times 10^{-4}d_0, 1.0479 \times 10^{-4}d_0)$. The corresponding values of impedance are shown in Fig. 2. It can be seen that the retrieved impedances for one, two, and three cells of SRR-rod metamaterial match well for most frequencies, while matching was not as satisfactory when the method in Ref. [4] was used (which corresponds to $x_1 = 0.5d_0$ in our formulation). We also calculated the impedance $z$ for the case of $x = (0, 0)$ and found that the results are almost the same as the optimized ones. We have corroborated this result with many other metamaterial thicknesses and geometries to eventually conclude empirically that the first effective boundary of a symmetric one-dimensional (1D) metamaterial [1,4,14] coincides with the first unit-cell boundary and the second effective boundary coincides with the last unit-cell boundary. For two-
dimensional (2D) [11,14] and asymmetric 1D metamaterials, no such rule could be found and the effective boundaries of the slab need to be determined from optimization.

C. Determination of n and z from S_{11} and S_{21}

It is a common method to determine z and n from Eqs. (2a) and (2b) with the requirement of Eqs. (3a) and (3b), where z and n are determined independently. However this method may fail in practice when z’ and n” are close to zero: A little perturbation of S_{11} and S_{21}, easily produced in experimental measurements or numerical simulations, may change the sign of z’ and n”, making it unreliable to apply the requirement of Eqs. (3a) and (3b), as discussed in Ref. [6]. In fact, z and n are related and we should use their relationship to determine the signs in Eqs. (2a) and (2b). In order to determine the correct sign of z, we distinguish two cases. The first is for |z’| ≥ δ, where δ is a positive number, for which we apply Eq. (3a). In the second case, for |z’| < δ, the sign of z is determined so that the corresponding refractive index n has a non-negative imaginary part, or equivalently |e^{inkd}| ≤ 1, where n is derived from Eqs. (1a) and (1b):

\[
e^{inkd} = \frac{S_{21}}{1 - S_{11} \frac{z - 1}{z + 1}}. \tag{6}
\]

Note that once we obtain the value of z, the value of e^{inkd} is obtained from Eq. (6), so that we avoid the sign ambiguity in Eq. (2b) [it can be proven that only one sign of the imaginary part in Eq. (2b) makes it equivalent to Eq. (6)]. Figure 3 shows the retrieved impedance using the method presented in this paper and using only the condition of Eq. (3a). It is noted that the discontinuities obtained when only applying the criterion z’ ≥ 0 are removed.

D. Determination of the branch of n’

We have presented in the previous sections a method of solving for z and n”, but n’ remains ambiguous because of the branches of logarithm function as seen in Eq. (4). In order to address this problem, it has been suggested to use a slab of small thickness and applying the requirement that \(\epsilon(f)\) and \(\mu(f)\) are continuous functions of frequency [4,5]. However, no further details on the continuity argument were provided. In our method, we determine the proper branch by using the mathematical continuity of the parameters, with special attention to possible discontinuities due to resonances. The method is an iterative one: Assuming we have obtained the value of the refractive index n(f_0) at frequency f_0, we obtain n^*(f_1) at the next frequency sample f_1 by expanding the function e^{in(f)kd/f_1}d in a Taylor series:

\[
e^{in(f_1)kd/f_1}d = e^{in(f_0)kd/f_0}d \left(1 + \Delta + \frac{1}{2} \Delta^2 \right), \tag{7}
\]

where \(\Delta = in(f_1)kd/f_1-d-in(f_0)kd/f_0d\) and k_0 denotes the wave number in free space at frequency f_0.

In Eq. (7), the branch index [m in Eq. (4)] of the real part of n(f_1) is the only unknown. Since the left-hand side of Eq. (7) is obtained from Eq. (6), Eq. (7) is a binomial function of the unknown n(f_1). Out of the two roots, one of them is an approximation of the true solution. Since we have obtained n^*(f_1), we choose the correct root among the two by comparing their imaginary parts with n’(f_1). The root whose imaginary part is closest to n’(f_1) is the correct one, and we denote it as n_0. Since n_0 is a good approximation of n(f_1), we choose the integer m in Eq. (4) so that n’(f_1) is as close to n_0 as possible.

The branch of n’ at the initial frequency is determined as follows: From \(\mu = nz\) and \(\epsilon = n/z\), we have

\[
\mu'' = n' z'' + n'' z', \tag{8a}
\]

\[
\epsilon'' = \frac{1}{|z|^2}(-n' z'' + n'' z'). \tag{8b}
\]

The requirements \(\mu'' \geq 0\) and \(\epsilon'' \geq 0\) lead to...
close to zero but \( z' \) is close to zero but does not, \( n' \) should be close to zero. At the initial frequency, we solve for the branch integer \( m \) satisfying Eq. (9). If there is only one solution, it is the correct branch. In case of multiple solutions, for each of the candidate branch index \( m \), we determine the value of \( n' \) at all subsequent frequencies using the above-mentioned iterative method. Because the requirement of Eq. (9) applies to \( n' \) at all frequencies, we use it to check the validity of \( n' \) at all frequencies produced by the candidate initial branch. Note in the special case when \( n'z' \) is close to zero but \( z'' \) is not, the checking process can easily be carried out. Therefore, the initial branch that satisfies Eq. (9) at both the initial frequency and the subsequent frequencies is the correct one.

For the SRR-rod structure, we found that there is a frequency region at which there is no branch index \( m \) satisfying Eq. (9). We call this frequency region the resonance band. The properties of the resonance band are still disputed by researchers. Some papers \([15–17]\) mention the existence of multiple modes in this region since the real part of \( n \) is large, yielding a wavelength comparable to or smaller than the unit size of the metamaterial thereby rendering the retrieval of the effective parameters of the metamaterials impossible. Other papers \([5,18]\) state that retrieval is possible and the retrieved permittivity \( \varepsilon \) has a negative imaginary part in the resonance band. In this paper, we do not address this issue and for this reason the retrieved results presented here are interrupted in frequency by the resonance region (see, for example, Fig. 4). In this case, since \( n(f) \) is not continuous through all frequencies, we have to determine the initial branches for two frequency regions: Below and above the resonance band. Note that below the resonant band, the retrieved branch index is zero, which confirms the validity of the traditional method used for low-frequency retrieval. The retrieved refractive indexes \( n \) for one, two, and three cells in the propagation direction are shown in Fig. 4, where the resonance band is seen to extend between 11 GHz and 12 GHz. We observe that the values of \( n \) for different cell numbers are identical above the resonant region. Below the resonant band, however, the retrieved \( n \) for one and two cells match well, but the result for three cells differs significantly from the previous two. This discrepancy is due to the small magnitude of \( S_{21} \) in this frequency band, as we shall discuss in the next section.

E. Sensitivity analysis

A close examination of the retrieved \( z \) and \( n \) for one, two, and three cells of metamaterial presented so far shows that the three results do not always match. There are two cases of discrepancies. The first is that the retrieved refractive index \( n \) for three cells of metamaterial does not match the value for one and two cells at low frequencies (5 GHz–11 GHz in Fig. 4). The second is that the impedance \( z \) appears to spike at some frequencies (around 12 GHz, 17 GHz, and 19.5 GHz in Fig. 2). We shall show here that these discrepancies are due to the sensitivity of \( z \) and \( n \) to the accuracy of \( S_{11} \) and \( S_{21} \).

The first case appears when \( |S_{21}| \) is close to zero. In the region below the resonance band, the transmission is usually small, especially for thicker metamaterials. From Eq. (2b), we see that \( S_{21} \) appears in the denominator, so that the values of \( n \) are very sensitive to small perturbations of \( S_{21} \). Yet, a small transmission has little influence on the retrieval of \( z \), which can be seen by computing:

\[
\frac{\partial z^2}{\partial S_{21}} = \frac{8S_{21}S_{11}}{[(1 - S_{11})^2 - S_{21}^2]^2},
\]

from which it is clear that a small \( |S_{21}| \) makes \( \partial z^2/\partial S_{21} \) small (approximately zero). In addition, we can see from Eq. (1b) that if \( n' \) is not small, \( S_{21} \) will decrease exponentially with \( d \), i.e., with an increasing number of cells in the propagation direction. Therefore, the smaller \( S_{21} \), the higher the computation and measurement relative errors, which leads to less accurate retrieval results.

The second case appears when \( S_{21}^2 \) is close to unity while \( S_{11} \) is close to zero. Similar to the first case, the denominator in the expression of \( z \) [see Eq. (2a)] approaches zero, thus making it difficult to retrieve \( z \). However, in this case, the value of \( n \) is stable. In this situation, instead of solving for \( n \).
and \( z \) which exactly satisfy Eqs. (1a) and (1b), we solve for the following inequalities:

\[
S_{11} - \frac{R_{01}(1 - e^{i2\pi k_0 d})}{1 - R_{01}^2 e^{i2\pi k_0 d}} \leq \delta_r, \quad (11a)
\]

\[
S_{21} - \frac{(1 - R_{01}^2) e^{i\pi k_0 d}}{1 - R_{01}^2 e^{i2\pi k_0 d}} \leq \delta_i, \quad (11b)
\]

where \( \delta_r \) and \( \delta_i \) are small positive numbers. Figure 5 shows the range of \( z \) satisfying Eqs. (11a) and (11b) for \( \delta_r = 0.015 \) and \( \delta_i = 0.0. \) At each frequency, all \( z \) having a real and imaginary parts between the bounds shown in Fig. 5 satisfy Eqs. (11a) and (11b). It can be seen that the magnitude of the spikes is within the tolerance error, which implies that they are due to the noise in the \( S_{11} \) and \( S_{21} \) data.

Finally, note that although the retrieved \( n \) and \( z \) for multiple cells may be different from that for one cell at some specific frequencies, the calculated \( S_{11} \) and \( S_{21} \) for multiple cells using the retrieved \( \varepsilon \) and \( \mu \) from one cell data match well with the \( S_{11} \) and \( S_{21} \) data computed for multiple cells directly from numerical simulation, as is illustrated in Fig. 6.

**F. Results**

The retrieved permittivity \( \varepsilon \) and permeability \( \mu \) of a one cell of SRR-rod structure of Fig. 1 are shown in Fig. 7. Note that although the results satisfy the condition \( \varepsilon'' \geq 0 \) and \( \mu'' \geq 0, \) the positive energy requirement \( \partial(\varepsilon\omega)/\partial\omega > 0 \) [19,20] is violated in the frequency band 12 GHz–12.2 GHz. As a result, the resonance band is extended to 11 GHz–12.2 GHz, as shown by the vertical dashed lines in Fig. 7(a). The value of \( \varepsilon \) and \( \mu \) are both negative in the frequency range 12.2 GHz–12.8 GHz, showing that in this band, the metamaterial exhibits a LH behavior. We also retrieved the effective parameters of four and five cells of metamaterial shown in Fig. 1, and the retrieval results are close to those for one, two, and three cells.

In addition, we also applied our method to retrieve the effective parameters of the structure taken from [14,21], as shown in the inset of Fig. 8(a). For a 1D structure, by matching the impedance \( z \) for one and two cells of the metamaterial using the previously described method, we obtain \( \bar{x}_{opt} = (2.2053 \times 10^{-3} d_0, 1.1356 \times 10^{-3} d_0), \) where \( d_0 \) is the length of unit cell. Again, we find that the two boundaries of the effective homogeneous medium are close to the outer unit-cell boundaries of the 1D metamaterial. Figure 8 shows the retrieved \( z, n, \varepsilon, \) and \( \mu \) for one cell of this metamaterial. It can be seen that the frequency range of 13.8 GHz–14.5 GHz is a LH band, which agrees with the conclusion in Ref. [14]. It should be noted, however, that for a 2D version of this metamaterial, the effective boundaries should be obtained from the optimization process, as they do not necessarily

**FIG. 6.** \( S_{11} \) and \( S_{21} \) (real and imaginary parts) for three cells: Comparison between FDTD results (dot line with *) and calculated \( S \) parameters based on the retrieved \( \varepsilon \) and \( \mu \) (solid line with □) for a one-cell metamaterial shown in Fig. 1.

**FIG. 7.** Retrieved \( \varepsilon \) and \( \mu \) (real and imaginary parts) for a one-cell metamaterial shown in Fig. 1. The vertical dashed lines denote the limits of the resonance band.
match the unit-cell boundaries of the metamaterial. Indeed, in this specific case, we obtain $\bar{x}_{\text{opt}} = (0.33110d_0, 0.30342d_0)$.

III. CONCLUSION

We have proposed an improved method to retrieve the effective parameters (index of refraction, impedance, permittivity, and permeability) of metamaterials from transmission and reflection data. The successful retrieval results for various metamaterial structures show the effectiveness of the method. Our main conclusions are as follows:

1) The first boundary and the thickness of the effective media can be determined by matching $z$ through all sample frequencies for different lengths of the slabs in the propagation direction. For symmetric 1D metamaterials, we have drawn the empirical conclusion that the first boundary coincides with the first boundary of the unit cell facing the incident wave, and the thickness of the effective medium is approximately equal to the number of unit cells multiplied by the length of a unit cell. For 2D and asymmetric 1D metamaterials, the effective boundaries have to be determined by optimization.

2) The requirement $z' \geq 0$ cannot be used directly for practical retrievals when $z'$ is close to zero because the numerical or measurement errors may flip the sign of $z'$, making the result unreliable. In this case, we have to determine the sign of $z$ by the value of its corresponding $n$ so that $n'' \geq 0$.

3) There is a resonance band characterized by the fact that the requirement $\mu'' \geq 0$ and $\varepsilon'' \geq 0$ cannot be satisfied at those frequencies. On each side of the resonance, the branch of $n'$ can be obtained by a Taylor expansion approach considering the fact that the refractive index $n$ is a continuous function of frequency. Since the refractive index $n$ at the initial frequency determines the values of $n'$ at the subsequent frequencies, we determine the branch of the real part of $n$ at the initial frequency by requiring that $\mu''$ and $\varepsilon''$ are non-negative across all the frequency band.

4) Due to the noise contained in the $S$ parameters, the retrieved $n$ and $z$ at some specific frequencies are not reliable, especially for thicker metamaterials at lower frequencies. In spite of this, the fact that $S_{11}$ and $S_{21}$ for multiple cells of metamaterial calculated from the retrieved $\varepsilon$ and $\mu$ for a unit-cell metamaterial match the $S_{11}$ and $S_{21}$ computed directly from numerical simulation confirms that the metamaterials can be treated as an effective homogeneous material.

ACKNOWLEDGMENTS

This work was supported by DARPA (Contract No. N00014-03-1-0716) and ONR (Contact No. N00014-01-1-0713).

射频和天线设计培训课程推荐

易迪拓培训(www.edatop.com)由数名来自于研发第一线的资深工程师发起成立，致力于专注于微波、射频、天线设计人才的培养。我们于2006年整合合并微波EDA网(www.mweda.com)，现已发展成为国内最大的微波射频和天线设计人才培养基地，成功推出多套微波射频以及天线设计经典培训课程和ADS、HFSS等专业软件使用培训课程，广受客户好评，并先后与人民邮电出版社、电子工业出版社合作出版了多本专业图书，帮助数万名工程师提升了专业技术能力。客户遍布中兴通讯、研通高频、埃威航电、国人通信等多家国内知名公司，以及台湾工业技术研究院、永业科技、全一电子等多家台湾地区企业。

易迪拓培训课程列表：http://www.edatop.com/peixun/rfe/129.html

射频工程师养成培训课程套装

该套装精选了射频专业基础培训课程、射频仿真设计培训课程和射频电路测量培训课程三个类别共30门视频培训课程和3本图书教材，旨在引领学员全面学习一个射频工程师需要熟悉、理解和掌握的专业知识和研发设计能力。通过套装的学习，能够让学员完全达到和胜任一个合格的射频工程师的要求...

课程网址：http://www.edatop.com/peixun/rfe/110.html

ADS学习培训课程套装

该套装是迄今国内最全面、最权威的ADS培训教程，共包含10门ADS学习培训课程。课程是由具有多年ADS使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了ADS在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用ADS，迅速提升个人技术能力，把ADS真正应用到实际研发工作中去，成为ADS设计专家...


HFSS学习培训课程套装

该套课程套装包含了本站全部HFSS培训课程，是迄今国内最全面、最专业的HFSS培训课程套装，可以帮助您从零开始，全面深入学习HFSS的各项功能和在多个方面的工程应用。购买套装，更可超值赠送3个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您的HFSS学习更加轻松顺畅...

课程网址：http://www.edatop.com/peixun/hfss/11.html
CST 学习培训课程套装

该培训套装由易迪拓培训联合微波 EDA 网共同推出，是最全面、系统、专业的 CST 微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习 CST 微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送 3 个月免费学习答疑…


HFSS 天线设计培训课程套装

套装包含 6 门视频课程和 1 本图书，课程从基础讲起，内容由浅入深，理论介绍和实际操作讲解相结合，全面系统的讲解了 HFSS 天线设计的全过程。是国内最全面、最专业的 HFSS 天线设计课程，可以帮助您快速学习掌握如何使用 HFSS 设计天线，让天线设计不再难…

课程网址：http://www.edatop.com/peixun/hfss/122.html

13.56MHz NFC/RFID 线圈天线设计培训课程套装

套装包含 4 门视频培训课程，培训将 13.56MHz 线圈天线设计原理和仿真设计实践相结合，全面系统地讲解了 13.56MHz 线圈天线的工作原理、设计方法、设计考量以及使用 HFSS 和 CST 仿真分析线圈天线的具体操作，同时还介绍了 13.56MHz 线圈天线匹配电路的设计和调试。通过该套课程的学习，可以帮助您快速学习掌握 13.56MHz 线圈天线及其匹配电路的原理、设计和调试…


我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，
※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求
※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

联系我们：

※ 易迪拓培训官网：http://www.edatop.com
※ 微波 EDA 网：http://www.mweda.com
※ 官方淘宝店：http://shop36920890.taobao.com