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Accurate Measurement of Q-Factors of Isolated Dielectric Resonators

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***Abstract*— In this paper, a set-up used to accurately measure the resonant frequencies and Q-factors of isolated dielectric resonators is described. The measured resonant frequencies and Q-factors of first five lowest order modes of two cylindrical dielectric resonators of relative permittivity 38.0 and 79.7 respectively are reported. The measured values are compared with those of rigorous numerical methods available in the literature.**

I. INTRODUCTION

THE knowledge of resonant characteristics of isolated dielectric bodies is of interest for remote sensing applications. "Isolated" dielectric resonators are also potentially useful as antenna elements [1]. A number of rigorous numerical methods have been reported in the last decade for evaluating the resonant frequencies and radiation Q-factors of isolated cylindrical dielectric resonators [2]–[5]. However, to verify the accuracy of these methods, very few results on the measurements of these quantities are available in the literature. To the best of our knowledge, the results reported in [2] are the only available experimental results which give measured data on the resonant frequencies and Q-factors of the first five lowest order modes of an isolated cylindrical dielectric resonator of a specific dielectric constant and aspect ratio. These results also suffer from some limitations. For example, in the set-up reported in [2], the $\text{HEM}_{11\delta}$ mode, which is the lowest order hybrid mode was not observed. Further, the measured value of Q-factor of the $\text{HEM}_{21\delta}$ mode is lower than the theoretically predicted values by about 40%. In this paper, we report the results of our measurements of the resonant frequencies and Q-factors on two dielectric resonator samples having values of $\varepsilon_r = 38.0$ and 79.7 respectively. The quantities have been determined by measuring the radar cross section (RCS) of the dielectric resonator samples as a function of frequency. For the measurement of the Q-factor, an algorithm different from measurement of "half-power" frequencies has been used. The algorithm used in this paper is useful in determining if the measured resonator response corresponds to that of a "single" resonator. In our set-up, all the modes predicted by theory were easily observed. It was also found that interference may exist between the neighboring modes of isolated resonators, which may cause problems in determining the value of the Q-factor accurately. The measured values for the Q-factors are found to be in good agreement with theoretical values reported in the literature for all except one, for which the response was found to deviate significantly from that of a "single" resonator.

II. EXPERIMENTAL SET-UP

The radar cross section (RCS) of dielectric samples was measured as a function of frequency in an anechoic chamber of inside dimensions 6 m × 5 m × 4 m. The sample was placed on a tall tapered Styrofoam cylinder and was excited by a transmitting horn placed at a distance of about 1.2 m from the sample. A receiving horn was placed by the side of the transmitting horn to receive the signal scattered by the resonator. The transmitting and receiving horns were connected to two ports of a Wiltron 360 network analyzer. More details about the set-up are described in [6]. A stepped synthesized CW signal was fed to the transmitting horn. In the usual RCS measurements, the received signal in the frequency domain is first transformed into the time domain (impulse response). The time domain response is then gated to eliminate the spurious signals scattered by bodies other than the target. In our measurements, no such time gating was used. It was found that when time gating was used, a considerable error was introduced in the measurement of RCS at and around the resonant frequencies, especially for high-Q modes. This is due to the fact that a high-Q mode keeps "ringing" for a long time after an impulse is "incident" on it. Since the RCS of a target is directly proportional to the ratio of power picked by the receiver horn to that fed to the transmitting horn, the set-up used served as a "transmission cavity" method [7] of determining the resonant frequency and Q-factor. Further, since the transmitting and receiving horns are loosely coupled to the target, owing to the large distance between them and the target, the measured resonant frequencies and Q-factors are essentially the unloaded quantities measured in an "isolated" environment. It may be noted that if the power is coupled to the resonator using probes kept close to the resonator as used in the set-up described in [2], the condition of "isolated" environment is altered considerably, especially for the measurement of radiation Q-factor. The emphasis in this paper is, therefore, on the more accurate measurement of the radiation Q-factor.

III. ALGORITHM FOR MEASUREMENT OF Q-FACTOR

The most commonly used algorithm for the measurement of the Q-factor of a resonator is to measure the "half-power"

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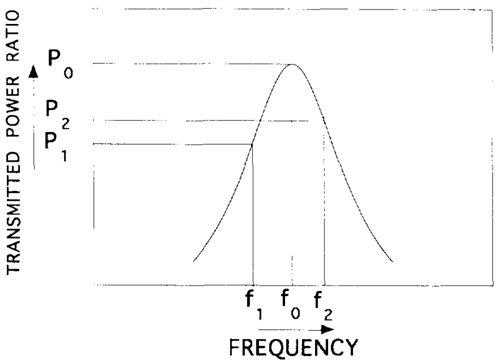

Fig. 1. Response of transmission through a "single" resonator cavity.

frequencies of the signal transmitted through the resonator. The algorithm is an accurate one if the response of the resonator corresponds to that of a "single" resonator at and around the resonance of the mode for which the measurements are being made. This is the case when there is no interference from the neighboring modes. However, the algorithm does not give any information whether the measured response deviates from that of a "single" resonator. The radiation Q-factors of the lowest order modes of an isolated resonator are quite low even for a moderately high value of dielectric constant of the resonator material. For example, for $\varepsilon_r = 38$, four lowest order modes have Q-factor less than 100, while their resonant frequencies lie relatively close to one another. Therefore, it is possible that the response of a particular mode of the resonator will be affected by the presence of neighboring modes. To check whether there was indeed such an interference from the neighboring modes, the algorithm described in [8] was used for the measurement of Q-factors. The algorithm can be summarized as follows.

The transmission response of a "single" resonator at and around the resonant frequency is shown in Fig. 1. If the power is measured at the resonant frequency f_0 and at arbitrary frequencies f_1 and f_2 on either side of the peak as shown in Fig. 1, the value of Q is given by [7]

$$Q = \frac{\left\{\sqrt{m_1^2 - 1} + \sqrt{m_2^2 - 1}\right\} f_0}{2(f_2 - f_1)} \tag{1}$$

In the above equation, the values of m_1^2 and m_2^2 are given by

$$m_1^2 = \frac{P_0}{P_1} \tag{2}$$

and

$$m_2^2 = \frac{P_0}{P_2} \tag{3}$$

where P_0, P_1 and P_2 denote the ratio of output power to the input power at the resonant frequency f_0 and at frequencies f_1 and f_2 respectively as shown in Fig. 1.

By measuring the response at M frequencies on one side of the resonance peak and at N frequencies on the other side, $M \times N$ values of Q are obtained. Assuming that there is no measurement error, all the $M \times N$ values must be same if the measured response corresponds to that of a "single" resonator. By computing the standard deviation of $M \times N$ values, an estimate of the deviation of the measured response from that of a "single" resonator can be obtained.

IV. RESULTS

Measurements were made on two cylindrical dielectric samples A and B. The sample A was made of Trans-Tech 8623 material. For the sample A, the values of ε_r and Q_d (Q-factor due to dielectric loss alone) as supplied by the manufacturer were equal to 79.7, and 3932 at 3 GHz respectively. The sample B was made of Trans-Tech 8812 material, and for this sample, the values of ε_r and Q_d were specified as equal to 38.0, and 7809 at 4.5 GHz respectively. The aspect ratio (height/diameter) of both the samples were chosen as equal to 0.438. This choice was made because for this value of aspect ratio, numerical results of a few rigorous methods [2]–[5] and experimental results [2] for a value of $\varepsilon_r = 38$ are available. The measured values of resonant frequencies and average Q-factors are shown in Table I for the resonator sample A. The measured values of Q-factor are labeled as Q_{tot}. The corresponding quantities for the resonator sample B are given in Table II. The number of frequency points chosen on either side of the peak, the standard deviation of the Q-factor and its coefficient of variation (coefficient of variation is defined as the value of standard deviation divided by the average value) are also shown in these tables. The values of m_1^2 and m_2^2 as given by (2) and (3) were chosen between 2 dB and 4 dB. The peaks of the $\text{HEM}_{11\delta}$, $\text{TM}_{01\delta}$ and $\text{HEM}_{21\delta}$ modes were observed when the electric field of the incident signal was polarized parallel to the axis of the resonator, while the peaks of the $\text{TE}_{01\delta}$ and $\text{HEM}_{12\delta}$ modes were observed when the incident signal was polarized perpendicular to the axis of the resonator. It is seen from Table I that the value of coefficient of variation of the Q-factor is quite low for all the modes for the resonator sample A, thus suggesting that the measured values are quite accurate. However, as seen from Table II, the values of coefficient of variation are generally higher for the modes of the sample B. This is attributed to the fact that for the sample B, the values of Q-factor are lower than the corresponding values for the sample A because of its lower ε_r value. It is thus expected that there will be a larger interference between neighboring modes of sample B than between the modes of sample A. In Fig. 2 the measured response of the $\text{TM}_{01\delta}$ and $\text{HEM}_{21\delta}$ modes is plotted for the resonator sample B. It can be seen that for the $\text{TM}_{01\delta}$ mode, the measured response deviates from that of a "single" resonator. This is reflected in the high value of the coefficient of variation (10.6%) for this mode. It was found in this case that due to interference between modes, the value of RCS did not drop by more than 8 dB in the frequency range between the peaks of $\text{HEM}_{11\delta}$ (res. freq. = 5.18 GHz) and $\text{TM}_{01\delta}$ (res. freq. = 6.133 GHz) modes. On the other hand, for the $\text{HEM}_{21\delta}$ mode, the measured response seems to correspond closely to that of a "single" resonator as shown in Fig. 2. This is in turn reflected in the low value of coefficient of variation obtained for this mode (1.0%). The corresponding measured response of the $\text{TM}_{01\delta}$ and $\text{HEM}_{21\delta}$

TABLE I

MEASURED RESONANT FREQUENCIES AND Q-FACTORS OF VARIOUS MODES OF AN ISOLATED CYLINDRICAL DIELECTRIC RESONATOR. $\epsilon_r = 79.7$, DIAMETER=10.29mm, HEIGHT=4.51mm. SD — STANDARD DEVIATION CV — COEFFICIENT OF VARIATION

Mode	Res. Freq. (GHz)	M,N	Qtot	SD	CV(%)	Qd[1]	Q_{rad}
$TE_{01\delta}$	3.4792	7,9	114.7	1.63	1.43	3250	118.9
$HEM_{11\delta}$	4.5600	16,21	76.42	1.26	1.65	2250	79.1
$HEM_{12\delta}$	4.7792	6,4	276.9	4.3	1.55	2100	319.0
$TE_{01\delta}$	5.4072	7,3	336.7	11.19	3.33	1750	416.9
$HEM_{11\delta}$	5.5368	2,1	937.5	5.05	0.54	1650	2171

[1] Found using manufacturer's data

TABLE II

MEASURED RESONANT FREQUENCIES AND Q-FACTORS OF VARIOUS MODES OF AN ISOLATED CYLINDRICAL DIELECTRIC RESONATOR. $\epsilon_r = 38.0$, DIAMETER=12.83mm, HEIGHT=5.62mm. SD — STANDARD DEVIATION CV — COEFFICIENT OF VARIATION

Mode	Res. Freq. (GHz)	M,N	Qtot	SD	CV(%)	Qd[1]	Q_{rad}
$TE_{01\delta}$	3.9672	18,43	46.2	2.38	5.15	8850	46.4
$HEM_{11\delta}$	5.1800	41,74	30.2	0.95	3.16	6780	30.3
$HEM_{12\delta}$	5.4032	46,22	43.0	1.45	3.37	6500	43.3
$TE_{01\delta}$	6.1328	72,13	57.5	6.07	10.56	5730	58.1
$HEM_{11\delta}$	6.3280	6,5	325.8	3.24	1.00	5550	346.1

[1] Found using manufacturer's data

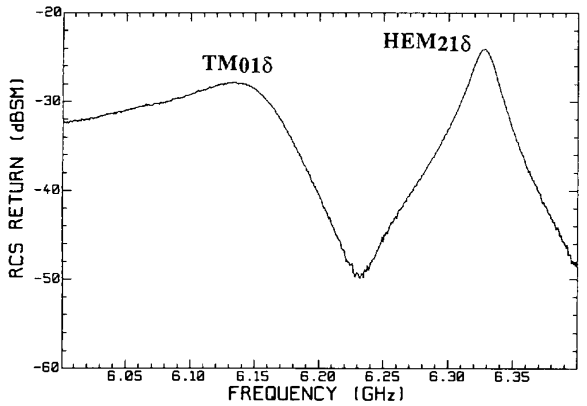

Fig. 2. Measured copolar radar cross-section (RCS) of isolated cylindrical resonator of parameters: $\epsilon_r = 38.0$, diameter = 12.83 mm, height = 5.62 mm. Incident signal is polarized parallel to the axis of the resonator.

modes for the resonator sample A is plotted in Fig. 3. It is seen that in this case, the responses of both modes seem to correspond closely to those of "single" resonators. This is attributed to the high values of the Q-factors of both these modes.

The measured values of Q-factor (labeled as Q_{tot}) are not due to radiation loss only and also contain contribution from the dielectric loss in the resonators. The total Q-factor Q_{tot} due to radiation and dielectric loss can be expressed as

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_{\text{rad}}} + \frac{1}{Q_d} \tag{4}$$

where Q_{rad} and Q_d are the Q-factors due to radiation and dielectric loss respectively. To compute the value of Q_{rad} from Q_{tot}, we need to know the value of Q_d.

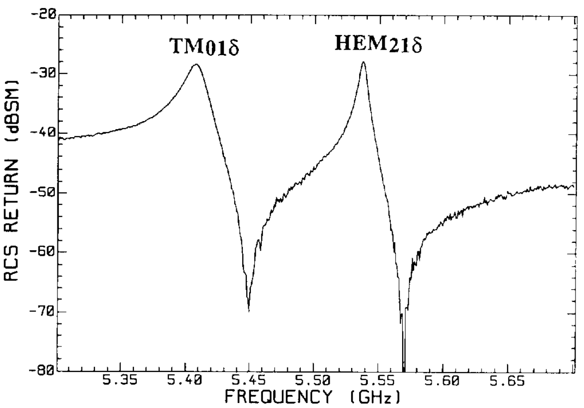

Fig. 3. Measured copolar radar cross-section (RCS) of isolated cylindrical resonator of parameters: $\epsilon_r = 79.7$, diameter = 10.29 mm, height = 4.51 mm. Incident signal is polarized parallel to the axis of the resonator.

TABLE III

COMPARISON OF MEASURED RADIATION Q-FACTORS OF AN ISOLATED CYLINDRICAL DIELECTRIC RESONATOR WITH THOSE OF RIGOROUS NUMERICAL METHODS AND EXPERIMENTAL RESULTS AVAILABLE IN THE LITERATURE. $\epsilon_r = 38$, ASPECT RATIO (HEIGHT/DIAMETER)=0.438

Mode	Measured Present	Meaured [2]	Theory [5]	Theory [3]	Theory [4]
$TE_{01\delta}$	46.4	51	45.8	40.8	47
$HEM_{11\delta}$	30.3	not obseved	30.7	30.85	31
$HEM_{12\delta}$	43.3	64	52.1	50.3	46
$TE_{01\delta}$	58.1	86	76.8	76.9	71
$HEM_{11\delta}$	346.1	204	327.1	337.66	324

The values of Q_d were supplied by the manufacturer at a single frequency for both the samples as mentioned earlier. Graphs showing the typical variation of Q_d as a function of frequency for the resonator materials used were also supplied by the manufacturer. From the given information, the values of Q_d were found at frequencies corresponding to the different resonant modes, and are given in Tables I and II for the two samples. It may be noted that to compute the values of Q_{rad} from Q_{tot} using (4), it is important to know the values of Q_d for the resonator sample A more accurately than those for the sample B. This is so, because for the sample A, the values of Q_d are not very large compared to the total Q-factor, especially for the higher order modes. Therefore, an error in the value of Q_d will cause an error of the same order in the computation of the value of Q_{rad}. To check the validity of the values of Q_d found using the data supplied by the manufacturer, the technique of measurement of Q_d as described in [9] was used. In this technique, the value of Q_d is computed by measuring the peak RCS of the lossy sample. At the frequency of the $TM_{01\delta}$ mode, the peak value of the RCS (σ) of a lossy dielectric sample of a sufficiently high permittivity is given by the following simple expression [10],

$$\sigma = \frac{9}{4\pi}\lambda_0^2\left(\frac{Q_{\text{tot}}}{Q_{\text{rad}}}\right)^2 \tag{5}$$

where λ_0 is the free space wavelength corresponding to the resonant frequency of the $TM_{01\delta}$ mode, and, Q_{tot} and Q_{rad}

TABLE IV
COMPARISON OF MEASURED VALUES OF NORMALIZED RESONANT WAVENUMBER (k_{0^a}) OF AN ISOLATED CYLINDRICAL DIELECTRIC RESONATOR WITH THOSE OF RIGOROUS NUMERICAL METHODS AND EXPERIMENTAL RESULTS AVAILABLE IN THE LITERATURE. $\varepsilon_r = 38$, ASPECT RATIO (HEIGHT/DIAMETER) = 0.438.

Mode	Measured Present	Meaured [2]	Theory [5]	Theory [3]	Theory [4]
$TE_{01\delta}$	0.533	0.533	0.531	0.534	0.535
$HEM_{11\delta}$	0.696	not observed	0.696	0.698	0.698
$HEM_{12\delta}$	0.726	0.730	0.730	0.731	0.731
$TE_{01\delta}$	0.824	0.836	0.827	0.829	0.827
$HEM_{11\delta}$	0.850	0.859	0.852	0.854	0.852

are the total and radiation Q-factors respectively as defined in (4). It has been shown that the formula of simple equation (5) is remarkably accurate for a value of ε_r as low as 38 [11]. In our set-up, the values of σ, resonant frequency and Q_{tot} are measured. Substituting these values in (5), the value of Q_{rad} can be computed. The value of Q_d can then be computed using (4). For the $TM_{01\delta}$ mode of sample A, the measured values of σ, resonant frequency and Q_{tot} are given in Fig. 3 and Table I. Using these values, the value of Q_d at 6.133 GHz (the resonant frequency of the $TM_{01\delta}$ mode) was found to be 1752, which is very close to that determined from the data supplied by the manufacturer as shown in Table I.

From the values given in Table II, it may be concluded that for the resonator sample having a value of $\varepsilon_r = 38.0$, the error in our measurement of the Q-factors is expected to be reasonably low for all modes except the $TM_{01\delta}$ mode. In Table III, the values of radiation Q-factor are compared with the experimental results reported in [2] and with the numerical results of rigorous methods [3]–[5] for the resonator sample having a value of $\varepsilon_r = 38.0$. It is seen that for the $HEM_{11\delta}$ and $HEM_{21\delta}$ modes, for which the various methods give nearly the same value of the Q-factor, our measured results for the radiation Q-factor are in very good agreement. For the $TE_{01\delta}$ and $HEM_{12\delta}$ modes, our measured results differ from those of theoretical methods by nearly the same amount as the results of different theoretical methods differ amongst themselves. The disagreement between our measured results and those of theory is found to be quite high for the $TM_{01\delta}$ mode. In this case, the error in our measurement is also expected to be high as already discussed. A suitable technique for the measurement of the Q-factor of the $TM_{01\delta}$ mode would be that, which selectively excites this mode. However, the design of such an excitation scheme for the resonator being placed in an "isolated" environment would be quite complicated.

The measured values of normalized resonant wavenumber (k_0a) are given in Table IV. It is seen that the disagreement between our measured results and those of rigorous methods is always less than 1%.

V. CONCLUSION

A set-up for the measurement of resonant frequencies and Q-factors of "isolated" dielectric resonators is described. The measured results for the Q-factor are found to be in good agreement with those of rigorous numerical methods for all modes except one, for which the measured response was found to deviate significantly from that of a "single" resonator.

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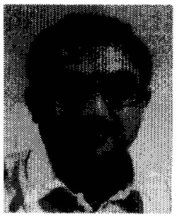

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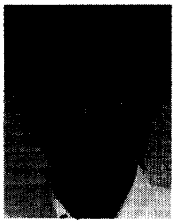
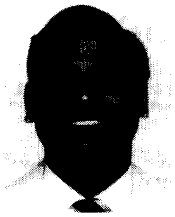


Shantnu Mishra was born in India in 1944. He received the M.Sc. degree in physics, the M.Sc. Tech degree in electronics, and the Ph.D. degree in electrical engineering from the University of Indore, India (1966), Birla Institute of Science and Technology, Pilani, India (1968) and McGill University, Montreal, Canada (1982), respectively.

He has been involved in the area of Electromagnetics, specifically radio frequency measurements since 1966. He served at the Central Electronics Engineering Research Institute, Pilani as a Research Fellow from 1968 to 1971, where he was involved in projects related to the design of microwave components and low cost antennas for television. From 1971 to 1974, he was a Research Associate at the Gordon McKay Laboratory of the Harvard University, Cambridge, Mass. where he was involved in the measurement of antennas for subsurface communications. He was a Research Assistant at the EE department of McGill University, Montreal Canada from 1974 to 1982 where he spent his time measuring EM field distributions in the vicinity of antennas and scatterers, and inside absorbers lined chambers. In 1982 he joined the National Research Council, Ottawa, Canada where he was engaged in upgrading, automating, computerizing, maintaining and operating antenna ranges and RCS and EMC measurements facilities until 1988. Since 1988 he has been working at the David Florida Laboratory at the Canadian Space Agency, Ottawa, Canada. His present interests include near and far field antenna and RCS measurements, EMC and PIM measurements and RCS analysis.



Dr. Prakash Bhartia (S'68–M'71–SM'76–F'89) was born in Calcutta, India. He received the B.Tech degree in Electrical Engineering from the Indian Institute of Technology, Bombay in 1966, and his M.Sc., and Ph.D. degrees from the University of Manitoba in Winnipeg in 1968 and 1971 respectively. He served as a Research Associate at the Manitoba from 1971 to 1973, when he joined the Faculty of Engineering at the University of Regina at Regina, Canada. In 1976, he was promoted to the rank of Associate Professor and served as Assistant Dean of Engineering. In September 1977, he joined the Defence Research Establishment Ottawa as a Defence Scientist, and in 1982 was appointed Section Head of the Electromagnetics Section, responsible for programs in navigation, electromagnetic compatibility and nuclear electromagnetic pulse effects. In February 1985, he was appointed Director Research and Development Air at National Defence Headquarters. From September 1985 to June 1986, he attended the National Defence College of Canada at Kingston and on his return was appointed Director Research and Development Communications and Space, where he served for three years. In September 1989, he was appointed Director of the Underwater Acoustics Division at the Defence Research Establishment Atlantic at Dartmouth, Nova Scotia, and in July 1991 he returned to Ottawa as Director of the Radar Division at Defence Research Establishment Ottawa. In July 1992 he was appointed Chief of the Defence Research Establishment Atlantic.

Dr. Bhartia has had considerable consulting experience with many companies while serving at the University and is the author of over 100 papers in the area of radar, microwave and millimeter wave circuits, components and transmission lines. He is also the coauthor of a number of books and has contributed chapters to other texts and holds a number of patents. He is a Fellow of the Institution of Electrical and Telecommunication Engineers and a member of a number of technical societies. He has served and continued to serve on the Editorial Board or as a reviewer for many scientific journals. He has served as a Director of the Canadian Microelectronics Centre, on the Queen's University Engineering Advisory Council, on the Tradex Management Inc. Board and currently on the Board of the Canadian Centre for Marine Communications and the Nova Scotia Premier's council in Applied Science and Technology. He is also Chairman of the Scientific Committee of National Representatives for SACLANTCEN in Italy.

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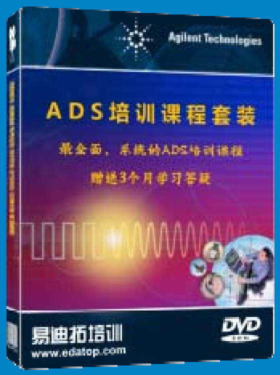
该套装精选了射频专业基础培训课程、射频仿真设计培训课程和射频电路测量培训课程三个类别共 30 门视频培训课程和 3 本图书教材；旨在引领学员全面学习一个射频工程师需要熟悉、理解和掌握的专业知识和研发设计能力。通过套装的学习，能够让学员完全达到和胜任一个合格的射频工程师的要求…

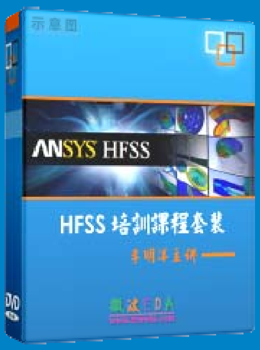
课程网址：http://www.edatop.com/peixun/rfe/110.html

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...

课程网址： http://www.edatop.com/peixun/ads/13.html





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 培训教程套装，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…

课程网址：http://www.edatop.com/peixun/cst/24.html

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…

详情浏览：http://www.edatop.com/peixun/antenna/116.html

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