From Kirchhoff Voltages to Maxwell Waves

Jaume Anguera [(1,2)], Aurora Andújar [(1)], and Xavier Vilasís [(2)]
[(1)] Fractus Antennas, Barcelona, Spain
[(2)] Telecommunication Engineering School, Universitat Ramon LLull, Barcelona, Spain
(Email: Jaume.anguera@salle.url.edu)

Abstract— **The paper introduces undergraduate students who have been in contact with Kirchhoff lows but not to Maxwell equations to introduce the field of electromagnetic radiation and guided waves. Using a simple circuit (a generator, a conductive line above a ground plane and a resistive load), easily understood from Kirchhoff laws when the size of the circuit is much less than the operating wavelength, students are introduced to guided waves and antennas when the frequency of the generator increases. The objective is to open a door to antenna and microwave engineering in a smooth manner prior to the use of Maxwell equations.**

Index Terms—**electromagnetics engineering education, antenna theory and microwaves undergraduate teaching.**

I. Introduction

Technical students meet first Kirchhoff laws than Maxwell equations due to the mathematical simplicity and the usefulness to analyze basic electric circuits. This implies that often voltages and currents are met well before electric and magnetic fields. Furthermore, first engineering lab experiments dealing with analog or digital electronics work with frequencies in the range of kHz, where the size of the circuit is much smaller than the operating wavelength (λ). For example, a circuit of 10cm at 10kHz is only $3.3 \cdot 10^{-6}\lambda$. Because of that, conductive wires used to connect components (resistors, inductors, capacitors, diodes, transistors, etc.) and integrated circuits are merely connecting means. In this sense, there is no need to worry about wire lengths, their bending, and proximity to ground or to other wires. In this framework, one may consider the circuits of Fig. 1 to be equivalent since $V_2=V_1$, $I_2=I_1$ and $Z_2=Z_1$: the length of the wire connecting Z_g to Z_{load} is irrelevant. However, as the frequency of operation increases, conductive wires connecting components (ex: resistors, transistors, capacitors, inductors, integrated circuits) no longer behave as expected. The general electromagnetic theory of Maxwell equations needs to be introduced. To easily present the huge potential of Maxwell equations, the paper presents an example of a conductive wire to show the phenomena of radiation and guided waves. Furthermore, an example of a guide wave (microstrip line) and an antenna (monopole) is given to motivate engineering students to pursue electromagnetic related courses such as electromagnetics, electromagnetic compatibility, microwave circuits, and antennas.

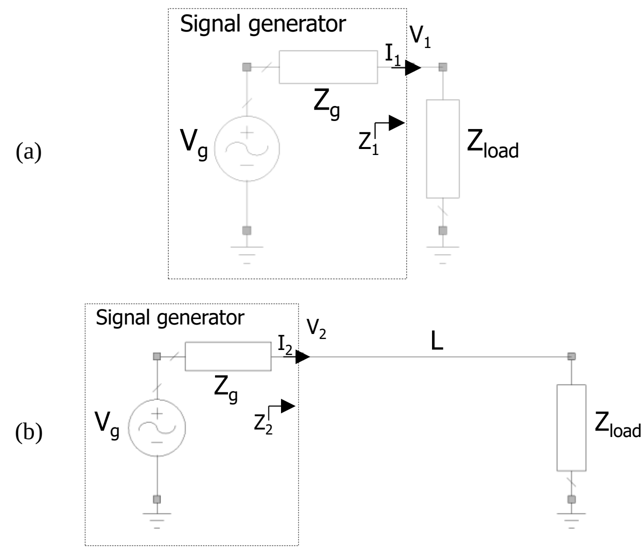


Fig. 1 a) A signal generator V_g with an operating frequency *f* and internal impedance Z_g is connected to an arbitrary impedance Z_{load}. b) The same as a) but using a conductive wire of length L

The natural evolution towards more complex circuits on a proto-board just keeps these simple principles and one often finds connections with arbitrary length wires, just as the picture in Fig. 2.

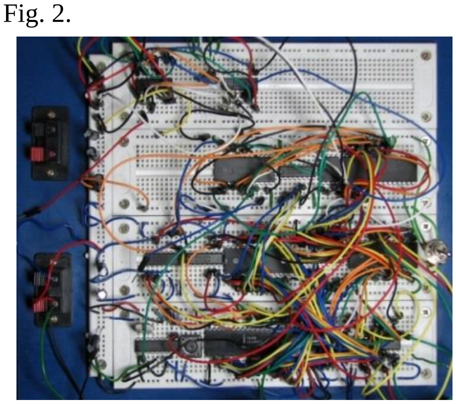


Fig. 2 A general example of a typical proto board connecting integrated circuits with conductive wires

After all this hard work in the low frequency domain, students go a step forward meeting electromagnetics. New concepts such as the electrical field E and magnetic field H are introduced, and they are shown to be related by the Maxwell equations. Despite the direct connection between these two domains, which in fact is the same one, they appear being disjoint, albeit contradictory. Electronics and Electrical engineering students may even wonder about the necessity of introducing the new concepts.

Many authors have proposed introductory methods to explain in an easy way the application of Maxwell equations to antenna and microwave engineering (Fig. 3). In [1], the author presents engineering problems (radomes, high-speed electronics, magnetic resonance imaging, etc.) treated by numerically solving Maxwell equations with a computer. Virtual lab tools for the understanding of wave phenomena in presented in [2]-[7]. In [8], author present antenna properties without equations using lab experiments. In [9]-[11], authors discuss on methods to introduce electromagnetics to undergraduate students such as using software tools and understanding real applications. Finally, [12] use simple equations relating electric and magnetic fields applied to particular situations such as the charge induced in a person due to a power line.

In order to introduce the benefits of the general theory of electrodynamics given by Maxwell equations to a student level, and illustrate how both descriptions connect, we propose to revisit a simple example of a conductive wire with length L above a ground plane (Fig. 1b) - (section 2). One observes the wire is not a useful mechanism to guide a voltage signal since some power is lost by radiation as the frequency increases. At this point, it results useful to introduce *Microwave Theory* to guide waves from one point to another (section 3). Moreover, since the unwanted radiation observed by the wire when increasing frequency may turn into a desired feature, it is attractive at this point to explain the need of *Antenna Theory* as the discipline to design telecommunication systems that efficiently radiate in the correct direction (section 4). This simple and familiar framework drives us through some of the key features of electromagnetic theory engineering.

(a) (b)

Fig. 3 a) James C. Maxwell, Scottish physicist (1831-1879), published the equations, known as Maxwell equations in the Philosophical Transactions of the Royal Society of London back in 1865 [13]. b) Gustav Kirchhoff, German physicist (1824-1887), proposed the fundamental behavior of voltages and currents in a circuit, known as Kirchhoff laws.

II. A Simple Example

As mentioned in the introduction, a simple and didactic way to illustrate the path from Kirchhoff laws to the use of Maxwell equations is studying a conductive wire connecting one generator having an internal impedance Z_g=50Ω to a load impedance Z_{load} with the same value (Fig. 4). Some quantities are defined to follow the analysis:

- P_{in}: input power, it will be fixed to 1W
- P_{load}: power delivered to the load
- P_{ref}: reflected power back to the generator
- P_{rad}: radiated power to space
- Z_{in}: input impedance seen from the generator plane

Note that P_{in}-P_{ref} is the power delivered to the wire and the load and $P_{in}=P_{ref}+P_{rad}+P_{load}$.

The results presented in this paper are obtained by numerical simulation using the software IE3D based on MoM (Method of Moments) which uses as mathematical kernel the numerical solution of Maxwell equations. IE3D solves Maxwell's equations in an integral form through the use of Green's functions. For educational purposes, open software can be used to reproduce the results presented here [14].

Maxwell equations (Table 1), a set of four equations, and all their mathematical manipulations, are the heart to understand electromagnetics and its applications such as microwave circuits and antennas. Such equations relate charges (ρ), currents ($\vec{J}$), electric and magnetic field ($\vec{E}$, $\vec{H}$), and matter of the medium where the wave is propagating (permittivity ε and permeability μ). In brief, Maxwell equations allows to find $\vec{E}$, and $\vec{H}$ for a given source (ρ, $\vec{J}$) given a particular geometry and mediums (ε, μ).

$\oint_S \vec{E}\cdot d\vec{S} = \dfrac{Q}{\varepsilon_0}$	Gauss's law
$\oint_S \vec{H}\cdot d\vec{S} = 0$	Gauss's law
$\oint_C \vec{E}\cdot d\vec{l} = -\mu\int_S \dfrac{d\vec{H}}{dt}\cdot d\vec{S}$	Faraday's law
$\oint_C \vec{H}\cdot d\vec{l} = \int_S \vec{J}\cdot d\vec{S} + \varepsilon\int_S \dfrac{d\vec{E}}{dt}\cdot d\vec{S}$	Ampère's law

Table 1 Maxwell equations in its integral form

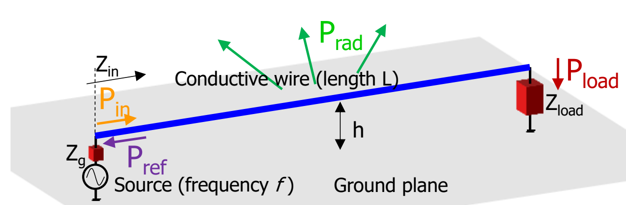


Fig. 4 A conductive planar wire 1mm width of length L=100mm is above a conductive ground plane (height h=5mm). At one end of the wire, there is an ideal generator (Z_g=50Ω internal impedance); at the other end, there is a load (Z_{load}=50Ω for this example)

At low frequencies, Kirchhoff laws allow to easily evaluate

P_{load} on the circuit of Fig. 4, if P_{in}=1W (this makes V_g=14.14V), P_{load}=1W. Therefore, $P_{ref}=P_{rad}$=0. At this point, we propose to analyze three cases: a first one where the frequency of the generator is 2MHz, a second one of 5.8GHz, and a third one of 10GHz (Fig. 5). Instead of looking at voltages and currents, we encourage to look at the electric field E around the wire.

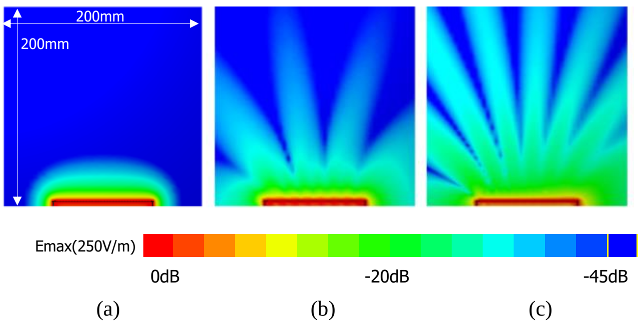


Fig. 5 Simulated electrical field for the circuit of Fig. 4 ($Z_g=Z_{load}$=50Ω, L=100mm, h=5mm) at three different frequencies of operation of the signal generator: a) 2MHz, L=0.0006λ, b) 5.8GHz, L=1.93λ c) 10GHz, L=3.33λ, being λ the operating wavelength

When the wire is small in terms of the wavelength (L<<λ), the electric field is concentrated between the wire and the ground. However, when the wire is comparable to λ, the field propagates far away (radiating field). Moreover, depending on the frequency, the field propagates in different directions (Fig. 5b, c). *Antenna Theory* is useful to analyze how radiation propagates to space and moreover, how to design a conductive body to effectively radiate in certain directions while minimizing in others (antenna design). And even more, antenna theory will allow us how to design non-conductive radiating bodies such as dielectric antennas.

To gain more physical insight, some results obtained with electromagnetic simulations are given (Fig. 6).

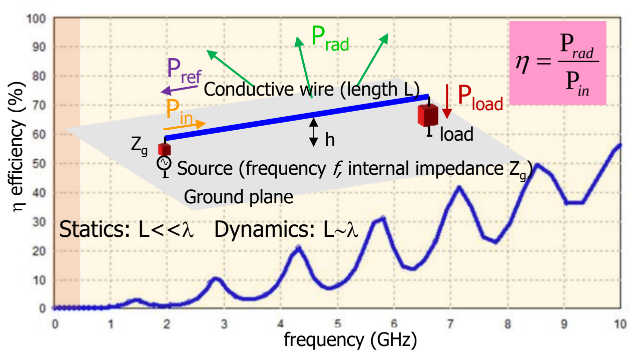


Fig. 6 Ratio of the radiated power P_{rad} over incident power P_{in} as a function of frequency for the circuit of Fig. 4 (L=100mm, h=5mm, $Z_g=Z_{load}$=50Ω)

At low frequencies where L<<λ, the radiated field is negligible, P_{rad}~0, so efficiency defined as the ratio between the radiated power and incident power is η~0. All the power goes from the generator to the load (if the load is matched as is the case since $Z_{in}=Z_{load}=Z_g$) – (Fig. 7). Therefore, a simple conductive wire is a good waveguide as all incident power is transmitted to the load (if there is conjugate matching) and therefore $P_{load}=P_{in}$. This region is where electric and magnetic fields are considered *static fields*. Although the fields are considered static, a wave still exist since we can associate a frequency to an electromagnetic wave. Therefore, the simple conductive wire can be considered a waveguide in the *static field* regime.

It is important to observe that power lines carrying high voltages do not radiate since the frequency of the signal is 50Hz, which makes λ=6000km. Any power line is much shorter than λ and as a consequence, the conductive wires carrying high voltages are efficient connecting means, just as the cables of the proto-board (Fig. 2). Yet, non-radiating does not mean that the electric near field (for example Fig. 5a) does not interact with near bodies. The discipline dealing with the interaction between electrical/magnetic fields with human bodies is studied in *Electromagnetic Dosimetry* and the effects of such fields over electronics circuits are studied in *Electromagnetic Compatibility*.

This raises the question of what happens when one moves from the low frequency region (L<<λ) to the higher frequency region (L comparable to λ and even much longer than λ).

At higher frequencies, where L~λ, the field is a radiating field, P_{rad}>0, so η>0. Thus, the conductive wire becomes an antenna and a bad waveguide. We need other structures to guide waves from one point to another to make P_{rad}=0 (microwave theory). Also, since the conductive wire radiates, special care needs to be taken to mitigate coupling with other circuits (electromagnetic compatibility). And finally, if we want to radiate waves in certain directions, we need tools to design the geometry of the conductive body (antenna theory). In this region, fields are *dynamic fields*.

It is also now interesting to observe that besides P_{rad}>0, when the wire L is comparable to the wavelength, P_{in} is different to $P_{rad}+P_{load}$. For instance, at 5.8GHz, η=26% (Fig. 6) and if we assume that $P_{in}=P_{rad}+P_{load}$=1W, this results in P_{rad}=0.26W and P_{load}=0.74W, but, based on Fig. 7, we observe that P_{load}=0.62W. What is now happening? The problem is that Z_{in} is no longer equal to Z_{load} as it was the case when L<<λ but different (Fig. 8). In fact, Z_{in}(5.8GHz)~74.2-3.79jΩ, that we can approximate to Z_{in}(5.8GHz)~74Ω causing an impedance mismatch. We may use Kirchhoff laws to solve the following scenario: assume Z_g=50Ω, connected to a $Z=Z_{in}$~74Ω (see Fig. 1a). If we know that considering conjugated matching conditions, that is, when $Z_{load}=Z_g^*$=50Ω, P_{in}=1W, this means that V_g (rms) applying Kirchhoff laws can be easily calculated from (1):

$$P_{in} = \left(\frac{V_g}{\left| Z_g + Z_{in} \right|} \right)^2 \mathbb{R}\left\{ Z_{in} \right\} \quad (1)$$

where $Z_g=Z_{in}$=50Ω. Since P_{in}=1W, V_g=14.14V.

Therefore, when Z_{in} is not 50 Ω but Z_{in}(5.8GHz)~74Ω, the power delivered to Z_{in} is 0.96W and not 1W, meaning a reflected power back to the generator of P_{ref}=0.04W. This 0.96W is equal to $P_{rad}+P_{load}$. Since P_{rad}/P_{in}=0.32, we obtain

P_{load}=0.64W which matches the numerical results in Fig. 7. It is interesting to observe that as expected P_{in}-P_{ref}=P_{rad}+P_{load}.

It is also worth noting that at low frequencies where L<<λ, the input impedance Z_{in} seen at the input port is equal to the impedance of the load, 50Ω in this case. However, as the frequency increases, Z_{in} changes as a function of frequency, not only the real part, but also the reactive part, being inductive, capacitive, and resonant (Fig. 8).

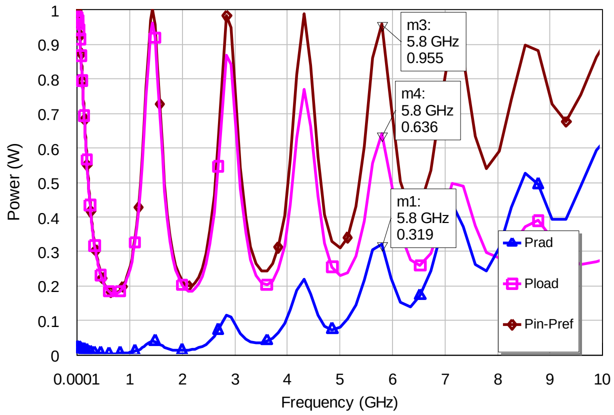


Fig. 7 P_{rad}, P_{load}, and power delivered to the line (P_{in}-P_{ref}) as a function of frequency. P_{in}=1W

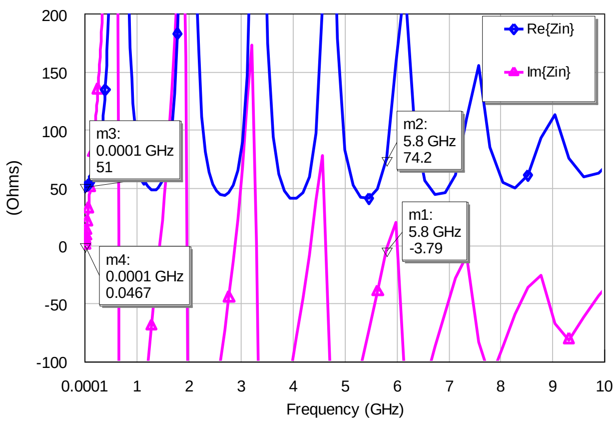


Fig. 8 Evolution of Z_{in} as a function of frequency for the circuit of Fig. 4 (L=10cm, h=0.5cm, Z_g=Z_{load}=50Ω)

As a summary, we pointed out several aspects that need to be considered when the wire is comparable to the wavelength: mismatching and radiation. To fully understand both phenomena, we need Microwave and Antenna Theory, both disciplines having as the *alma mater* Maxwell equations which should be used to manage these problems. And nature is richer than simple wires, with more complex bodies such as 2D and 3D structures, making this field even more attractive and useful for practical applications [15]-[16].

III. A WAVEGUIDE

In the previous example, we have observed that a simple conductive wire is a good waveguide at low frequencies where the length of the wire L is much smaller that the wavelength λ of the operating frequency: all incident power reaches the load as long as the impedance load Z_{load} matches the conjugated impedance of the generator Z_g. But, as frequency increases, not all the incident power P_{in} is transmitted to the load, but some part is lost in forms of radiation and some part is lost due to reflection caused by mismatching. Then, when an electronic circuit is comparable to the wavelength, how a waveguide can be designed to guide power from one point to another? *Electromagnetics* and *microwave theory* are the disciplines that will allow us to understand and design waveguides to minimize radiation loss and mismatching [17]. As an illustrative example, a particular waveguide is introduced: a microstrip line (Fig. 9). The reason is that a microstrip line is very similar to the conductive wire shown here. It comprises a planar conductive line of width W (4.8mm) length L (100mm) printed on a substrate (ε_r=1, tanδ=0.001) of height h (1mm). Understanding substrates such as fiber glass when designing analog and digital circuits in the low frequency domain becomes important in this framework. At low frequencies, the term lossy substrate is totally useless. The substrate acts simply as a support material to host all the circuitry. Thus, this example is relevant since besides radiation loss and mismatching, substrate losses appear as a new concept.

By a proper design of the microstrip line, choosing the width W, height h and the permittivity (ε_r) of the substrate, the loss due to radiation can be minimized, that is, P_{rad}~0 as it is observed for a wide frequency range (Fig. 9). The variables W, h, and ε_r, determines the characteristic impedance, a concept that is essential for the correct design of microwave circuits. In this example, the characteristic impedance is 50Ω.

The electrical field for the same frequencies of operation as the original wire shows that most of the field is concentrated around the strip (Fig. 10) and therefore, radiated power P_{rad} is negligible, which is aligned with the results obtained in Fig. 9.

As a particular comment of Fig. 9, in practice, a lumped element as the 50Ω load in the microstrip line is placed on top of the substrate and then connected to ground with a via hole [17].

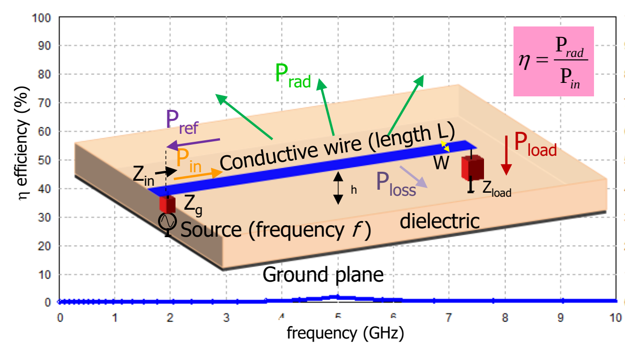


Fig. 9 Microstrip line: a conductive strip of width W (4.8mm) and length L (100mm) printed over a substrate (dielectric) of height h (1mm) backed by a ground plane (conductive plane).

The source has an internal impedance Z_g. Z_{in} is the impedance seen at the input of the microstrip line. The microstrip line ends with a load Z_{load}=Z_g=50Ω. P_{in}=1W, P_{ref} is the reflected power back to the generator, P_{rad} is the radiated power, P_{loss} is the power lost in the dielectric, and P_{load} is the power delivered to the load. P_{in}-P_{ref}=P_{rad}+P_{loss}+P_{load}

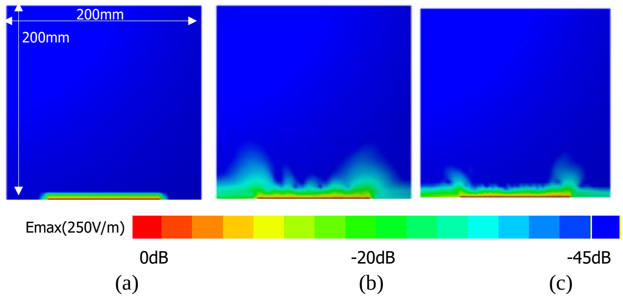


Fig. 10 Electrical field for the microstrip line of Fig. 9 for three different frequencies of operation: a) 2MHz, L=0.0006λ, b) 5.8GHz, L=1.93λ c) 10GHz, L=3.33λ

It is important to note that the input impedance Z_{in} is almost equal to 50Ω (Fig. 11), therefore P_{ref}=0, so P_{in}=1W should go to P_{load}, but it is not (Fig. 12).

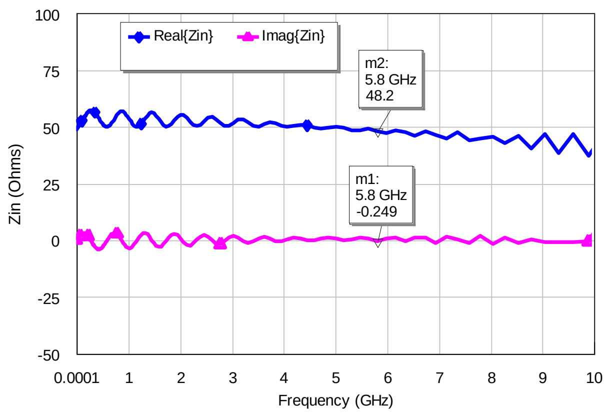


Fig. 11 Input impedance as a function of frequency for the microstrip line of Fig. 9

Assuming that P_{rad}=0 (the line is not radiating), and P_{ref}=0 (perfect matching) it is interesting to compute P_{load} (Fig. 12). We observe that P_{load} is not 1W (P_{in}) but approximately 0.95W. A new term call power loss in the substrate appears into the scene. This power loss is due to the non-zero loss tangent of the substrate (tanδ=0.001 for this example). Therefore, approximately 0.05W is lost in the substrate and not reaching the load. The quality of materials plays an important role to design not only guide waves but also antennas since the power lost in the substrate should be minimized as much as possible. For instance, deteriorating the loss tangent to 0.01, makes P_{load}(5.8GHz) dropping from 0.95W to 0.72W. In addition, conductor loss is also relevant. However, from a practical perspective, an engineering has a pull of substrates with different tanδ whereas conductor is usually fixed, being copper as one of the most used in practice.

Finally, it is worth pointing that in this case P_{ref}=0 because the microstrip transmission line has been designed in such a way that Z_{in}=Z_{load}=50Ω which is the same as Z_g. But, if the microstrip line is not correctly designed, besides P_{loss}, mismatching also appears. Furthermore, in practical scenarios, P_{in} should be transferred not to a 50 Ω broadband load but to a complex load depending on frequency. This may be the case of transferring power of a generator to an antenna having a complex impedance Z(*f*) as a function of frequency *f*. Therefore, the waveguide connecting the generator with the antenna has not only to minimize the loss due to radiation and loss in the substrate but also to match $Z_{antenna}(f)$ to Z_g. As this is a challenge task: the line must match the complex impedance load to the impedance to the generator. Since the load is dependent on frequency, the line can adopt different shapes to match the load to the generator as a certain frequency band. Moreover, not all the pressure goes to the waveguide but also to the antenna in such a way to have a $Z_{antenna}(f)$ to be easily matched to Z_g. This means that an antenna has the huge responsibility to efficiently radiate and receive electromagnetic waves in certain directions, minimize in others and at the same time to provide an impedance to minimize mismatching with the generator (either a transmitter or a receiver).

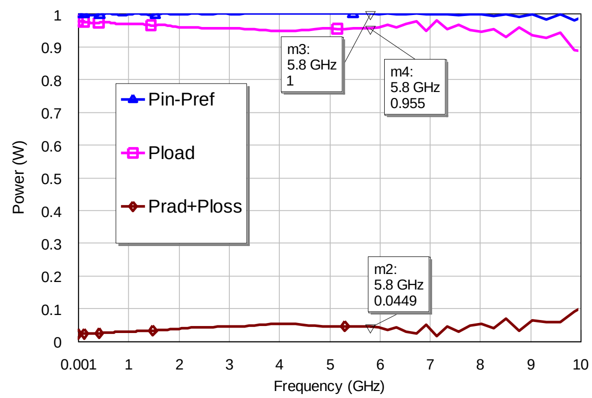


Fig. 12 P_{rad}+P_{loss}, P_{load}, and power delivered to the line (P_{in}-P_{ref}), as a function of frequency. P_{in}=1W for the microstrip line of Fig. 9 (tanδ=0.001)

IV. AN ANTENNA

So far, we have shown that a simple conductive wire is a good waveguide if its length is much less than the operating wavelength. However, when it is comparable to it, it is not a good guiding wave since power is lost in forms of radiation and mismatching. But now, we may turn the question and study how to make a conductive wire to intentionally radiate. As an introduction to antenna theory, we propose the following example using the conductive wire vertically placed on an infinite ground plane (Fig. 13).

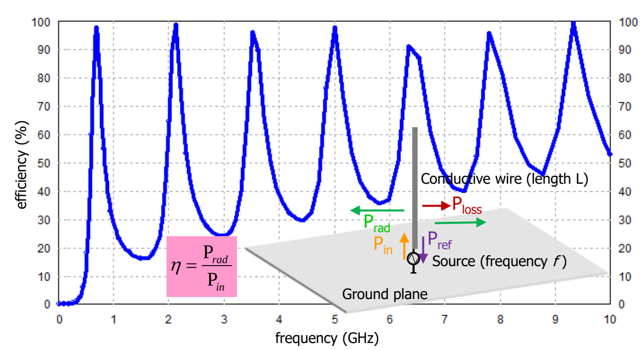


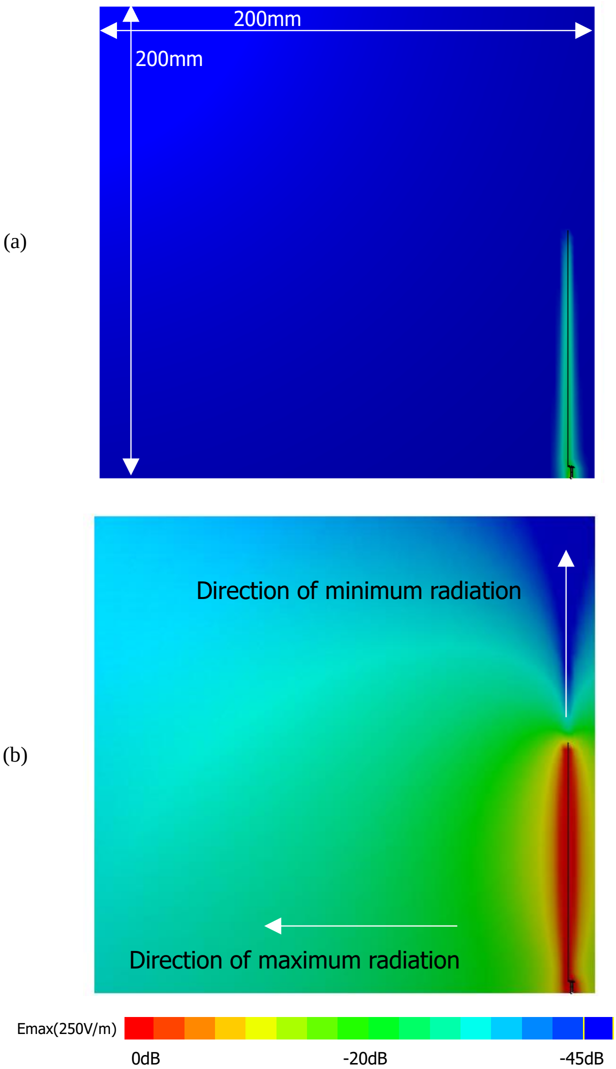
Fig. 13 A vertical conductive wire (monopole antenna) and its computed efficiency. Wire length L=10cm

To show how radiation takes place, the conductive wire is vertically placed (Fig. 13). This kind of antenna is called a monopole.

Before, in the waveguide case, the objective was to minimize P_{rad}; on the contrary, now, we want to maximized it, that is, the goal is to have P_{rad} as closer to P_{in} as possible so all the incident power is radiated to space and not lost due to mismatching or losses in the conductor due to Joule's effect.

(a)

(b)



(a) (b)

Fig. 14 a) Electric field for a vertical conductive wire of L=10cm at the frequency of 2MHz over an infinite horizontal ground plane; b) the same case but increasing the frequency to 700MHz (L=10cm, is approximately λ/4 at 700MHz, being the antenna called a quarter-wave monopole)

It is first worth to analyze from a qualitative point of view the fields around the wire in the low frequency region where the wire is very small in terms of the wavelength and in the other, where the wire is comparable to it (Fig. 14). For the electrically short monopole case (L<<λ), the conductive wire is not radiating; the electric field is mainly concentrated along the wire. However, for the quarter-wave monopole, there is radiation, and in fact an interesting kind of radiation which maximizes power in the horizontal plane and provides a null pointing to the sky. Thus, when the wire is comparable to the wavelength, it may radiate and the most interesting thing: we can shape such radiation using antenna engineering so as to have maximum radiated power in certain directions while minimizing in others [18]-[19].

It is interesting to analyze the problem using Kirchhoff laws at the very low frequency region (Fig. 15). One concludes that at the very low frequency region where the effect of the conductive wire can be neglected, the input impedance is so high that we have just an open circuit and thus, P_{rad}=0, which is supported by observing Fig. 13. But, when the frequency increases, P_{rad} increases and eventually at certain frequencies is close to P_{in}. This is because we cannot model the conductive wire as a zero-impedance component but as an impedance with a real and imaginary part depending on frequency (Fig. 16). In this way, when the conductive wire is comparable to the wavelength, such impedance models the antenna from a circuit perspective. Thus, knowing such impedance is not only useful to analyze how much of the incident power will be radiated but also how much will be reflected to the generator due to mismatch.

It is important to use here Maxwell equations to understand the radiation phenomena (Table 1). Once we excite the conductive wire with a certain source ($\vec{J}$), from Ampère's law, a magnetic field $\vec{H}$ is created. If this $\vec{H}$ has some dependence on time, from Faraday's law, it will create a certain $\vec{E}$. Now, if this new $\vec{E}$ depends on time, it will now support a $\vec{H}$ from Ampère's law. This loop repeats and thus, an electromagnetic wave is created. This means, that graphically speaking, a time varying $\vec{E}$ wave creates a time varying $\vec{H}$ wave and the other way around, creating an electromagnetic wave. This is fact possible to the term $\varepsilon\int_S \frac{d\vec{E}}{dt}\,d\vec{S}$ introduced by Maxwell which was of paramount importance to demonstrate the existence of electromagnetic waves. Based on both Faraday's and Ampere's law, it is also observed that the larger the time variation of both $\vec{E}$ and $\vec{H}$ field, the easier the radiation will be. A rapid time variation is equivalent to high frequency which is aligned with the results presented here.

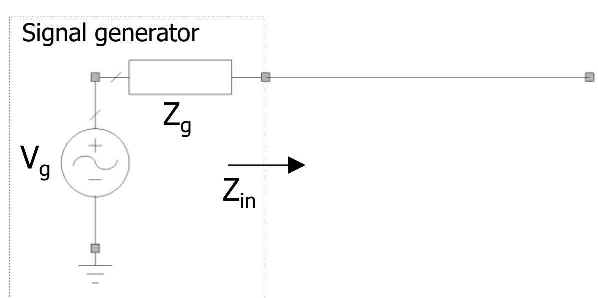


Fig. 15 Electric circuit to analyze the input impedance Z_{in} at very low frequencies

The input impedance of the conductive wire as a function of frequency presents a real part and imaginary part (Fig. 16). At certain frequencies, the imaginary part is zero receiving the name of resonant frequencies. Also, if at this frequency, the real part is the same as the 50 Ohms of the generator, based on Kirchhoff laws, there is no mismatch and all the incident power is transmitted to the impedance modeling the antenna.

The amount of radiated power depends on the quality of the conductive material of the wire. Therefore, it may happen that although $Z_{antenna}$=50 Ohms which is the same as the impedance as the generator, not all power is radiated. At this point, we can split the real part of $Z_{antenna}$ in two: one that considers the radiation to space and another that considers the losses due to heating of the conductive wire by Joule's effect. The antenna impedance $Z_{antenna}$ can be measured using a vector network analyzer, an equipment one finds in Lab-related activities to the field of microwave theory and antennas (Fig. 17a). However, in order to measure which part belong to radiation, we use other special equipment called anechoic chamber (Fig. 17b). In this way, with the vector network analyzer we can measure the impedance of the antenna to understand how much power is reflected to the generator due to mismatching and how much power to the antenna. Then, part of the power delivered to the antenna will be radiated to space and other part lost. An anechoic chamber is used to measure much power is delivered to space over the input power (as the efficiency shown in this paper), besides other parameters such how the antenna radiates such power into space (radiation pattern).

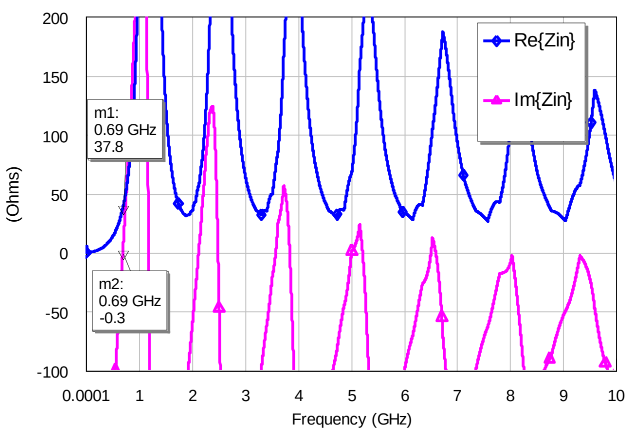


Fig. 16 Input impedance of the monopole as a function of frequency. Re stands for real part and Im stands for imaginary part

There are many attractive things to learn having practical applications; to name a few: miniaturization of antennas and microwave circuits, multiband antennas for wireless devices such as smartphones, smartwatches, smartmeters, compact antennas for vehicles, integrated antennas and circuits in human bodies, wearable antennas, large antenna for base stations, satellite, radio astronomy, radar antennas, antennas for biomedicine, robotics, etc.

Going back to the conductive issue, it is important to take materials into account: substrates and conductors are essential part of microwave circuits and antennas as well as important parameters such as permittivity, permeability, and conductivity. This overview should provide a good dose of motivation to study electromagnetics and all related subjects such as microwave and antennas and its applications

(a)

(b)

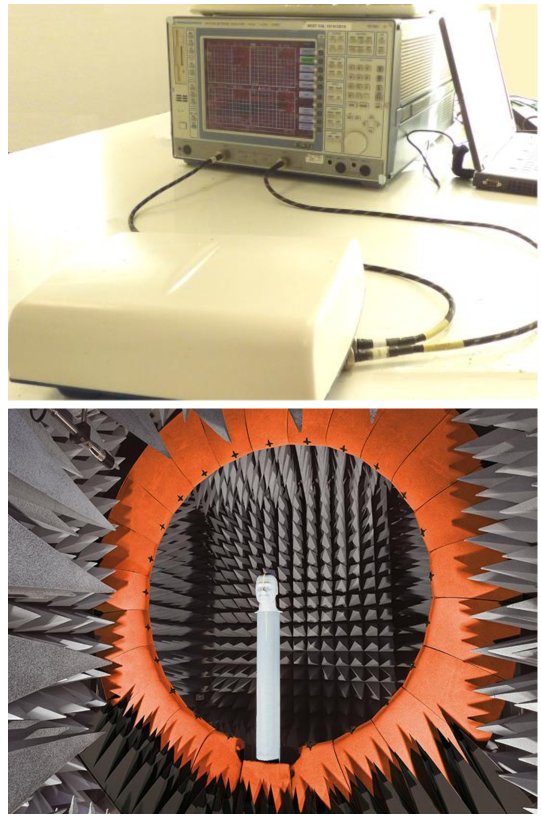


Fig. 17 a) Vector network analyzer useful to measure impedance and related parameters of microwave circuits and antennas; b) anechoic chamber (Satimo Stargate-32) employed to measure how an antenna radiates into space – the antenna is placed at the center of the gate. Several receiving antennas are located along the gate to measure the electromagnetic radiation from an antenna

V. CONCLUSIONS

To introduce the usefulness of Maxwell equations, a conductive wire above a ground plane connected in one end to a generator and to the other end to a load has been used.

When the electronics circuits are comparable to the wavelength, concepts such as radiation, losses, and mismatch come into play.

Antennas are designed with conductive/dielectric bodies to efficiently radiate in some directions, minimize in others and at the same time to minimize power reflected to the generator in order to radiate more efficiently. Also, there are mechanisms to guide waves from one point to another minimizing mismatch losses as well as losses in the conductor or dielectrics.

A proper knowledge of *Antenna and Microwave Engineering*, which rely on Maxwell equations, is indispensable for today's telecommunication/electrical and electronics engineers since wireless applications are growing at an exponential speed.

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Jaume Anguera, IEEE Fellow, was born in Vinaròs, Spain. Co-Founder and CTO at Fractus Antennas (2017-up to date) and Associate Professor at Universitat Ramon LLull (1999-up to date), Barcelona, Spain. Previously, he was R&D Manager at Fractus (1999-2017). Author of more than 240 scientific journal and conference papers and authored seven books. Inventor of more than 140 granted antenna patents many of them licensed to wireless companies. He worked in South Korea (Fractus-Korea) designing small and multiband antennas for the mobile industry (e.g. Samsung and LG). In Korea, he headed up the research team. One of his main tasks was to provide training, education and development of the team's core competency, and to provide R&D vision to address the rapidly growing mobile device market.

He has supervised more than 110 bachelor/master/PhD thesis and served as a chairman at various antenna conferences.

With more than 21 years of experience in industrial design for small and multiband antennas for wireless devices, he has received awards such as New Faces of Engineering (IEEE), finalist with other inventors at the European Patent Award for the contribution of small antennas for the mobile industry as well as two awards for the best PhD thesis given by COIT (Colegio Oficial Ingenieros de Telecomunicación) and Telefónica. Dr. Anguera has been participating in more than 21 funded national and international research projects valued more than 6M€ (e.g. H2020), many of them as a principal researcher. He is associate editor at IEEE Open Journal on Antennas and Propagation, an Associate Editor at Electronics Letters, member of the editorial board at several scientific journals and reviewer at prestigious journals (IEEE, IET, PIER).

Aurora Andújar, M-IEEE was born in Barcelona, Spain. Co-founder and Senior Product Manager and New Business Development Manager at Fractus Antennas (2017 – up to date). She received the Bachelor's degree in Telecommunication Engineering in 2005, the Master degree in 2007, and PhD degree in 2013 from the Universitat Politècnica de Catalunya (UPC).

From 2007 to 2017 she worked with Fractus as R&D Engineer where she was in charge of the development of technological projects focused on the design of miniature and multiband antennas for wireless devices. She was also involved in the maintenance and growth of the patent portfolio of the company, including the development, writing, and prosecution of new inventions and patents (2007-2013).

Since 2009 she is leading research projects in the antenna field for wireless devices in the collaborative university-industry framework. In 2013, she moved to the Products and Service Department where she was in charge of the development and release of new antenna products for wireless devices.

Dr. Andújar has more than 13 years of experience in the antenna industry. Author of more than 30 patents in the antenna field. She has published more than 85 papers in scientific journal, international, and national conferences. She has directed more than 40 bachelor and master thesis.

She received two awards for the best PhD thesis given by COIT (Colegio Oficial Ingenieros de Telecomunicación) as well as special awards given by UPC.

Xavier Vilasís is a professor at the Salle-URL and vice-dean of the Doctoral School.

He is IP of the DS4DS (Data Science for the Digital Society Research Group), member of the LHCb collaboration and member of the IEEE Cellular Neural Networks and Array Computing Technical Committee. He has directed 8 doctoral theses, 10 research projects with competitive financing, published more than 300 articles in magazines and has contributed to more than 50 conferences.

He is the coordinator of the Doctoral Program at La Salle-URL. He has been a professor of Advanced Mathematics, Probability, Numerical Analysis, Calculus, Physics, optical communications, neural networks, Control Theory, Data Analysis and advanced Statistics.

He has a degree in Physics from U. Barcelona (1989) and a PhD in Physics from U. Barcelona (1993). He is also a PDG (General Management Program) by IESE (2016). He has been an FPI fellow at the Ministry of Education and Science (1990-1993), assistant professor at U. Barcelona (1994), analyst of Applications in Advanced Computing (1994-1996) and since 1996, is La Salle, URL. His research areas are Particle Physics, HEP, Data Science, data analysis, neural networks, machine learning and Artificial Intelligence.