Interacting Short Dipole Antennas

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Abstract. This is a didactical text written to students of Physics and Engineering to investigate the interchange of electromagnetic radiation between two *short dipole antennas*. These phenomena can be observed in lessons and public sessions in the "Laboratório de Demonstrações EWH" of the Institute of Physics of the University of São Paulo (IFUSP).

Key words: *short dipole antennas; emission and reception; essential aspects.*

(I)Introduction.

A large number of excellent papers and books have been written about emission and reception of electromagnetic waves by dipole antennas. We have recently written a didactical text, a **"laboratory guide",** showing basic aspects of radiation emission by dipole antennas.[1] In **Section 1** is done a brief review about the emission by a *short dipole antenna* (SDA). In **Section 2** is studied the case of two interacting SDA: one emitting radiation and the other receiving this radiation.

(1) Short Dipole Antenna (Half-Wave Center-Fed Antenna).

In **Figure (1.1)** is shown the schematic representations of a **center-fed half-wave dipole antenna** or simply **short dipole antenna** (SDA).

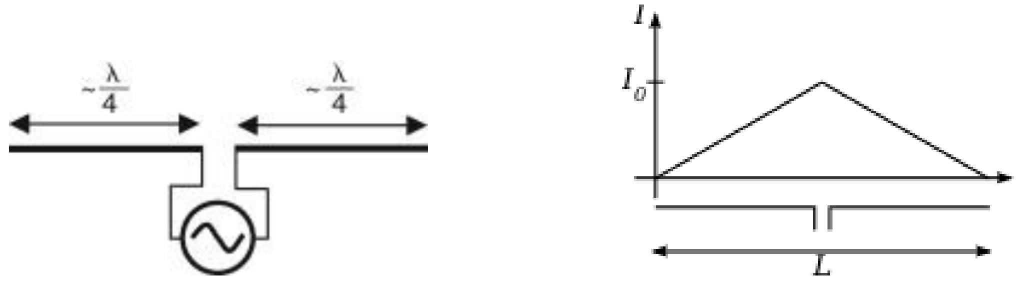

Figure (1.1). Schematic representation of a **center-fed half-wave dipole antenna** or, for simplicity**, short dipole antenna**. The right scheme roughly shows the current in the arms: it increases from zero up to I_o at L/2 (feed point) and after decreases from I_o up to zero at L.[3,4]

According to the left side of **Figure (1.1),** the SDA is composed by two conducting wires[2,3] powered by an alternating current generator with frequency $\omega = 2\pi/T$. Each wire has a length $L \sim \lambda/4$, where $\lambda = cT = 2\pi/\omega$. The right figure shows the current I in the arms: it increases from zero up to I_o at L/2 (feed point) and after decreases from I_o up to zero at L. As seen in preceding paper,[1] the fundamental resonance of a thin linear conductor with size L occurs at a frequency wavelength $\lambda/2 = L$.

In **Figure (1.2)** is shown typical SDA used in our laboratory.

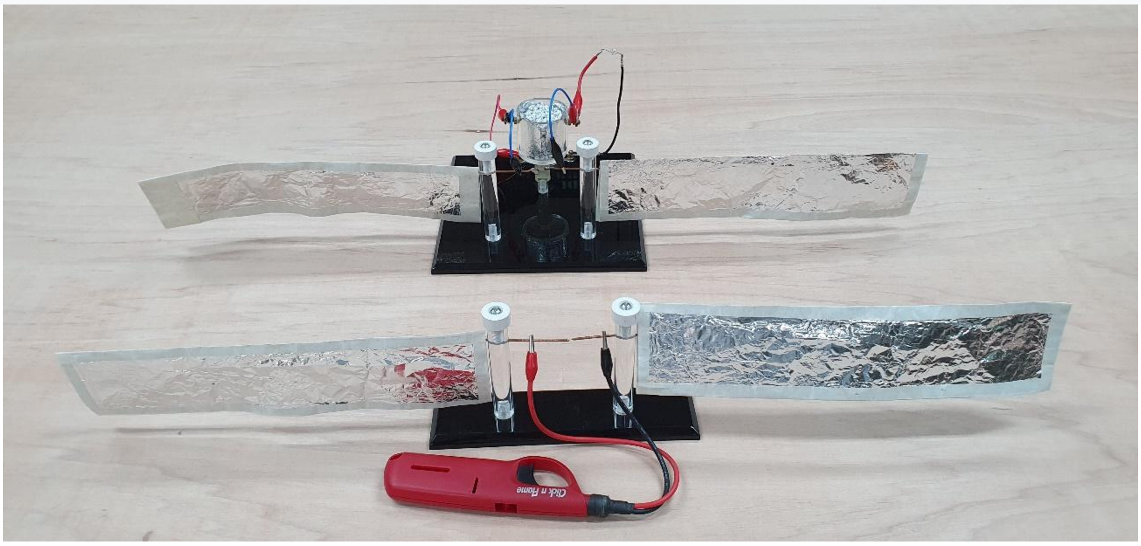

Figure (1.2). Emitter (below) and receiver (above) dipole antenna.

We use a "homemade" Branly's coherer [6] as a wave receiver and a common piezoelectric spark generator as an emitter. it is a simple teaching device that is easy to build. In **Figure (1.3)** the electrical diagram of the emitter and receiver dipole antennas.

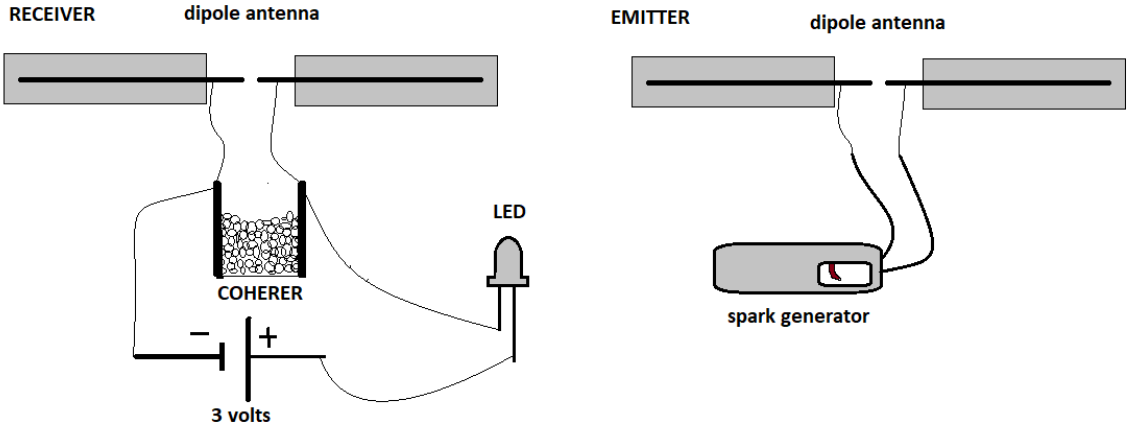

Figure (1.3). Emitter (right) and receiver (left) diagrams.

The Branly’s coherer is an excellent apparatus for illustrating the emission, propagation, and reception of electromagnetic waves.

We use copper wire and kitchen aluminum foil as antennas. The spark generator is a common piezoelectric igniter. The receiver is a Branly’s coherer constructed with hundreds small aluminum foil balls (**Figure (1.4)**) inside a container with 2 insulated electrodes (**Figure (1.5)**).

Figure (1.4). Small aluminum balls

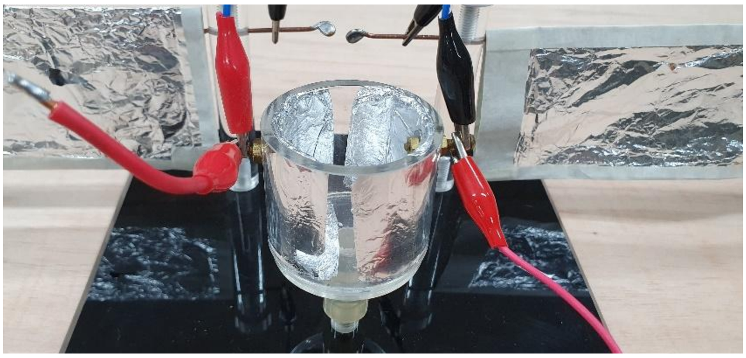

Figure (1.5a). Container with electrodes (empty)

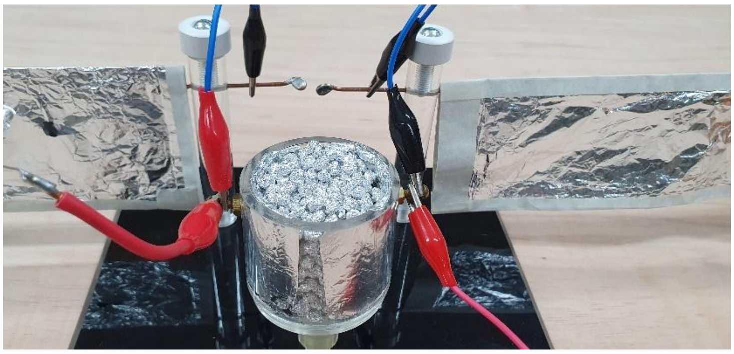

Figure (1.5b). Container with electrodes (full of aluminum balls)

Initially the electrical resistance at the terminals of the container with the balls is about hundreds of mega-ohms (**Figure (1.6a)**).

Figure (1.6a). Coherer resistance before the spark in the emitter (375 MΩ)

After the emitter sparks, the electrical resistance drops to just a few ohms (**Figure (1.6b)**).

Figure (1.6b). Resistance after the spark in the emitter (1.1 Ω)

In this way, initially, the LED is off because of the high electrical resistance of the cohesive device. But when receiving an electromagnetic wave pulse generated in the emitter's spark by the receiver antenna, the LED lights up because the coherer resistance decreases millions of times.

Therefore, the LED connected in series with the coherer will light up after the spark, as shown the **Figure (1.7)**.

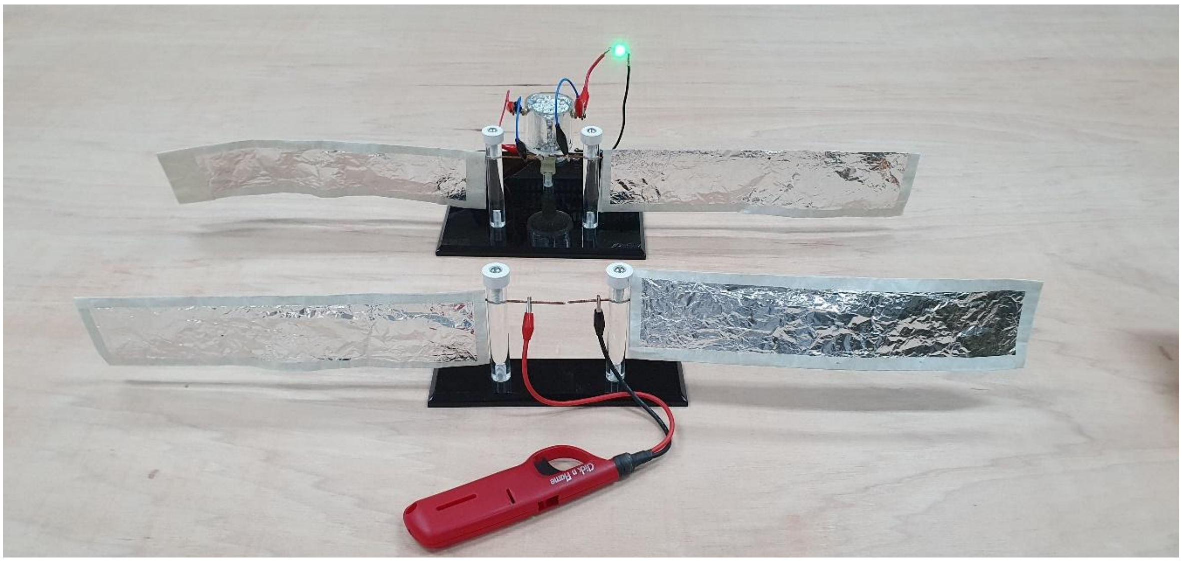

Figure (1.7). The LED will light up after the emitter spark

This apparatus can work with the emitter positioned a few tens of meters away from the receiver, as shown in **Figure (1.8)**.

Figure (1.8). Emitter far away, a few tens of meters from the receiver.

(2) Electric Current Induced by the Radiation.

Detailed calculations of the electromagnetic radiation emitted by a **short dipole antenna** can be seen in our preceding paper.[1]

We analyze now the case of two SDA: one antenna E is emitting **radiation** and another R is receiving this radiation. Will be estimated the electric current induced in R due the incident radiation emitted by E**.**

Let us consider a very simple geometrical configuration between two SDA to analyze the radiation interchange between them. So, let us take the E and R antennas parallel to a z-axis with the feed points at O and O´

along the X axis (see **Figure 2.1**). The R antenna is in the *radiation zone* of E, that is, at distance $\xi >> L$. As the radiation has a doughnut-shaped pattern [1] its incidence is essentially normal to the R.

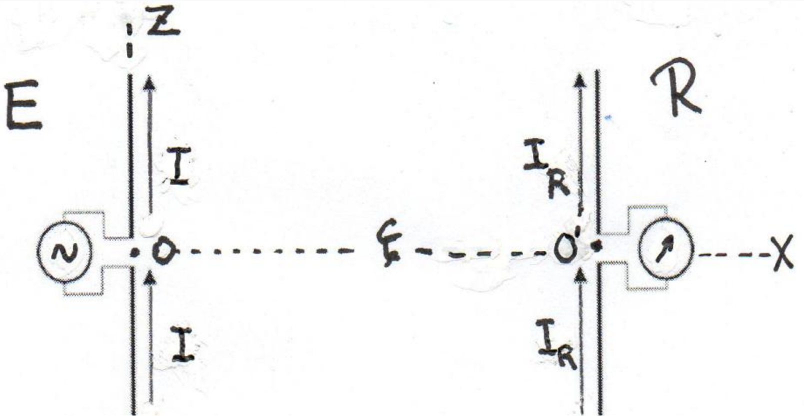

Figure (2.1). Radiating E and receiving R antennas parallel along the z-axis. The R antenna is in the radiation zone of E.

(2.1) Calculation of electric current induced in the R antenna.

According to **Eq. (3.9)** shown in our preceding paper,[1] the electric field emitted by E, which is incident on R wire, would be given by

$$\mathbf{E}_R(\xi,\theta,t) \approx i(\zeta_o\, I\, Lk/4\pi\xi)\, e^{i(k\xi-\omega t)} \sin(\theta)\, \boldsymbol{z} \qquad (2.1),$$

where $\zeta_o = [\mu_o/\varepsilon_o]^{1/2} \approx 377\ \Omega$ is the "vacuum impedance", L the wire length of E, I the E current, $k = 2\pi/\lambda$ and ξ the distance between O and O´; θ goes from 0 and π and $\boldsymbol{z}$ is the unit vector along the z-axis. In reference [3] is shown an animated diagram of a half-wave dipole antenna receiving a radio wave. The electric field of the incoming wave pushes the electrons in the rods back and forth, charging the ends alternately positive and negative.

If σ is the electric conductivity of the R wire, $\mathbf{E}_R$ will induce on R an electric current $I_{\mathbf{R}}(\xi,t)$ given by[4](see **Appendix**).

$$I_R(\xi,t) \sim \sigma\, \mathrm{Re}\{E_R(\xi,t)\} \approx (\sigma\, \zeta_o\, I\, Lk/2\pi\xi) \cos(k\xi-\omega t) \qquad (2.2).$$

Note that Eq. (2.2) gives a satisfactory estimation of $I_R(\xi,t)$ only when the feed centers O and O´ are aligned along the x-axis and when $\sin\theta \approx 1$.

The majority of antenna designs are based on the *resonance* principle. This implies that the reception would be more efficient when the incident wavelength $L \sim 2\lambda$, which occurs with SDA.[5]

Now, let us assume that the E and R wires are along lines forming an angle Ψ between them. In this case the current I_R would be given by the projection of $\mathbf{E}_R(\xi,t)$ on the R wire. That is, the I_R current would be

$$I_{\mathbf{R}}(\xi,t,\Psi) \approx I_{\mathbf{R}}(\xi,t)\,|\cos(\Psi)| \approx (\sigma\,\zeta_o\,I\,Lk/2\pi\xi)\,\cos(k\xi-\omega t)\,|\cos(\Psi)| \quad (2.3).$$

The angle Ψ is due to a rotation of the R wire around the x-axis or to an inclination of the R wire relative to the x-axis.

(3) Experimental results.

As in our laboratory there are only simple electronic equipments it is not possible to confirm detailed predictions given by Eq. (2.3). Only the main aspects will be confirmed, as will be seen in what follows.

The E and R antennas are of copper wires with length L = 20 cm, diameter d ~ 1 mm. To improve the transmission range, we placed aluminum foil strips covering the copper wires. These strips are 7 cm wide and 30 cm long, both on the emitter and on the receiver antenna.

In the emitting antenna are generated peaks of currents I in very short time intervals Δt. These current peaks detected by R will be indicated by I*. The electric field that induces this current also causes another interesting effect on Branly's coherer connected to the receiving antenna: the container with the aluminum balls, which used to be practically an insulator, becomes a good conductor after the detection of the electric field, as we saw earlier. As the coherer is connected in series with an LED and a battery, it is lit indicating that the receiving antenna has detected the signal emitted by the sending antenna. To turn off the LED, just tap the coherer container to make it behave like an insulator again.

In these peaks the average frequencies and wavelengths of the detected radiation will be represented by ω^* and λ^* , respectively. So, the detected $I_{\mathbf{R}}(\xi,t,\Psi)$, defined by Eq.(2.3), would be given by

$$I^*_{\mathbf{R}}(\xi,\Psi) \approx (\sigma\,\zeta_o\,I^*\,L/\lambda^*\xi)\,|\cos(\Psi)| \quad (3.1),$$

where $\zeta_o = [\mu_o/\varepsilon_o]^{1/2} \approx 377\ \Omega$.

The E and R antennas were positioned, as shown in **Fig. (2.1),** with distances ξ going from 5 up to 20 m.

For distances $\xi \le 5$ m, for **rotational angles** around the x-axis, we verified that

$\Psi = 0 \rightarrow I^*_{\mathbf{R}}(\xi, \Psi) \neq 0$
$\Psi = \pm \pi/2 \rightarrow I^*_{\mathbf{R}}(\xi, \Psi) = 0$,

and for **inclination angles** along the x-axis we verified that,

$\Psi = 0 \rightarrow I^*_{\mathbf{R}}(\xi,\Psi) = 0$
$\Psi = \pi/2 \rightarrow I^*_{\mathbf{R}}(\xi,\Psi) \neq 0$,
$\Psi = \pi \rightarrow I^*_{\mathbf{R}}(\xi,\Psi) = 0$,

in agreement with predictions of the Eq. (3.1).

For intermediate angles, that is, with Ψ between 0, π/2 and π we observe that I^*_R decreases, but our measurement instruments are not sufficiently accurate to determine how much.

For distances $\xi > 5$ m **Eq. (3.1)** begins to be invalid because $\mathbf{E}_R(\xi,\theta,t)$ incident on R, given by eq.(2.1), leaves to be tangent to the R wire. That is, θ begins to be different from $\theta = \pi/2$.

APPENDIX.

(A.1) Electromagnetic Wave Propagation in Conductors.[4]

The x-directed propagation of a plane electromagnetic wave, linearly polarized in the z-direction, through an Ohmic conductor of conductivity σ is governed by the equations:[4]

$$\partial E_z/\partial t + (\sigma/\varepsilon_o)E_z = - (1/\varepsilon_o)\, \partial H_y/\partial x$$

$$\partial H_y/\partial t = - (1/\mu_o)\, \partial E_z/\partial x \qquad (A.1).$$

For good conductors, which satisfies the inequality $\sigma >> \varepsilon_o\omega$, the first term on the left-hand side of Eq. (A.1) is negligible with respect of the second term, and the previous two equations reduce to

$$E_z \approx - (1/\sigma)\, \partial H_y/\partial x$$

$$\partial H_y/\partial t = - (1/\mu_o)\, \partial E_z/\partial x \qquad (A.2).$$

These equations can be solved to give

$$E_z(x,t) = E_o\, e^{-x/d} \cos(kx - \omega t)$$

$$H_y(x,t) = (E_o/Z)\, e^{-x/d} \cos(kx - \omega t - \pi/4) \qquad (A.3),$$

where $d = (2/\mu_o\omega\sigma)$ is the *skin-depth* and $Z = (\mu_o\omega/\sigma)^{1/2}$ the impedance of the medium. For a typical metallic conductor such as Copper whose at room temperature has $\sigma \sim 6.0\ 10^7/\Omega$m we verify that $d \approx 6/\sqrt{f(Hz)}$ cm. It follows that $d \approx 6$ cm for 1 Hz and $d \approx 2$ mm for 1kHz. The impedance Z for $\sigma \sim 6\ 10^7/\Omega$m and $f \sim 6\ 10^{14}$ Hz is given by $Z \approx 10$. Showing that, in this case, electric effects are dominant, according to Eqs.(A.3).

The average energy flux $< S_z >$ absorbed by the antenna is given by[4]

$$< S_z > = < E_z H_y > = |E_z|^2/\sqrt{8}Z = E_o^2\, e^{-2x/d} / Z\sqrt{8} \qquad (A.4),$$

showing that only part of the incident energy is absorbed. Usually the main part of the incident energy is reflected. For $\sigma \sim 6\ 10^7/\Omega.\mathrm{m}$ and $\omega \sim 10^{14}$ rad/s the reflection coefficient[4] defined by $R = (E_r/E_i)^{1/2} = 1 - (8\varepsilon_o\omega/\sigma)^{1/2}$ is equal to $R \approx 1 - 10^{-2} = 0.09$, that is, 90 % is reflected.

***Acknowledgements**. The author thanks the librarian Virginia de Paiva for his invaluable assistance in the publication of this paper.*

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