Received: 19 November 2020 | Revised: 12 February 2021 | Accepted: 12 February 2021

DOI: 10.1002/eng2.12392

SHORT COMMUNICATION

WILEY

Delay time in the transfer of modulation between microwave beams

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Abstract

Measurements of delay time relative to the signal transferred from a modulated beam F_2 to an unmodulated one F_1, both of which operate with a microwave carrier at ∼9.3 GHz, are reported and interpreted. The observed behavior is open to two possible interpretations: one is based on a purely stochastic model that consists of zigzag random paths; the other is based on a more conventional electromagnetic approach, although it maintains some of the characteristics of the stochastic model. The anomalous behaviors here studied can have significant applications in photonics and electro-optics.

KEYWORDS

delay time, microwaves, stochastic

1 | INTRODUCTION

An anomaly consisting of an unexpected transfer of modulation from a modulated beam to an unmodulated one has been well demonstrated and evidenced in previous and recent works.[1-3] Only in a recent paper, however, the origin of this phenomenon has become better focused and a role played by stochastic processes hypothesized.[4]

However, notwithstanding the detailed results reported therein, one aspect remained unexplored, namely, the behavior of the delay-time relative to the signal transferred to the unmodulated beam. An aspect, this latter, that is of particular importance in relation to fundamental, but even to practical applications. Although in a preliminary report the hypothesis of superluminal behavior was given,[2] more accurate results, as those reported in the present work, support completely different conclusions.

The connection with superluminality, as carefully examined in a variety of situations in Reference 5, is based on the fact that the involved mechanism—namely a stochastic process[6]—is essentially the same; other situations of superluminal behavior were already reported, see f.i. References 7-10.

The purpose of the present work is simply that of reporting the results of the delay-time measurements. The data obtained show a rather unexpected, irregular behavior which, in a certain sense, reinforces the hypothesis of the presence of stochastic processes. This represents a novel result since it is presumably the first time in which a direct experimental demonstration of a stochastic behavior in this kind of systems, as already theoretically predicted, has been observed. This will enable us not only to formulate a model based on such an assumption but also to compare it with a more conventional electromagnetic approach.

A third way of considering these results is offered by Feynman’s transition-element theory,[11] which can be considered an alternative to the stochastic approach, even in relation to the weak-measurement theory.[12] Even if the intensity of the detected signal is decidedly less than the one of the emitted beams, the number of the involved photons continues to be very high, so that its behavior remains essentially classical.

Although the interest in this kind of results is mainly of fundamental type, it is not excluded the possibility of an applicative perspective. As for what concerns the applications of these anomalous behaviors (mainly but not only the superluminal one[13]), we can recall that they are largely connected to photonics and electro-optics. In this context, dispersive engineering researches have been conducted on metamaterials that are currently considered a new class of materials for manipulating waves.[14,15] In particular, many potential engineering applications based on the transformation electromagnetics have benefit from superluminal studies.[16] These include the possibility of transferring superluminal signal over short distance[17,18] and the superluminal propagation through one-dimensional photonic crystal.[19]

2 | EXPERIMENT

The experimental set-up is essentially the same as the one adopted in Reference 4 and is reported in Figure 1. Measurements of delay time, versus the distance ρ ($\geq \rho_i$, ρ_i being the initial value of ρ) between the F_1 (c.w.) launcher (9×8 cm^2 horn antenna) and receiver (6×8 cm^2 horn antenna), were performed by comparing the signals taken both before the F_2 modulated beam (14×11 cm^2 horn antenna) and after the receiver antenna, respectively. Both beams were derived by the same generator at $\sim$ 9.3 GHz; the F_2 beam was modulated by a squared wave with a repetition frequency Ω of $\sim$ 800 Hz. The delay measurements were performed over the rise or the fall time (of the order of nanoseconds) of the square wave. The accuracy of the measure was of a few tens of picoseconds, when using a temporal-resolution digital oscilloscope (Tektronix 2440 or TDS 680B). Results relative to four determinations, each one obtained as an average between rise- and fall-time measurements, are reported in Figures 2 and 3. The F_2 beam is obtained as the near field emerging from a composed pupil that shows a relatively narrow diagram: see Fig. 2 in Reference 20. This implies that the region of overlapping with the F_1 beam (~4 cm), region in which a typical interference occurs, is smaller as compared to previous cases (~10 cm).[1-3]

3 | THEORETICAL MODELS

As previously anticipated, we note a rather irregular shape in the delay time. Such behavior is possibly open to different interpretations:

1. One, which is more properly based on stochastic processes, interprets the delay time as resulting from checkerboard or zigzag random paths experienced by the "particle": a kind of motion that is equivalent to the telegrapher's equation.[6] Alternatively, we can adopt the transition-element theory.[11]
2. A more conventional electromagnetic approach interprets the delay data as showing an undulating shape, with a relatively long spatial period, that results from the "competition" between the two fields (F_1 and F_2), in accordance

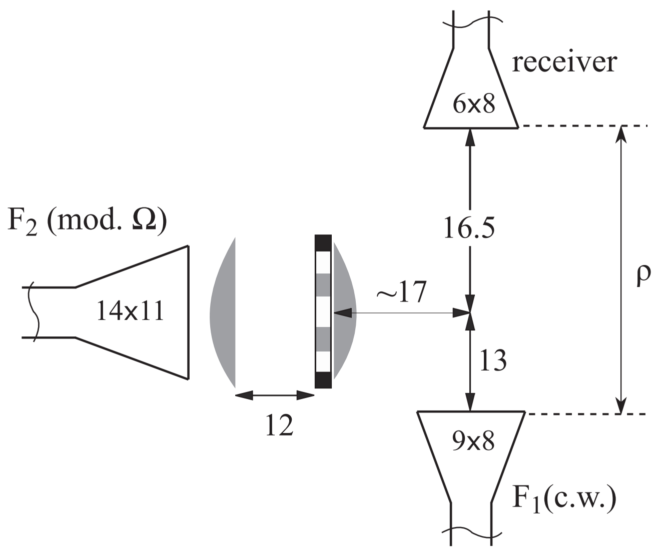

FIGURE 1 The experimental set-up, which operates at 9.3 GHz, consists of two horn antennas as launchers for the F_1 c.w. field and the F_2, Ω modulated field, traveling through a composed pupil. The latter consists of two paraffin lenses and a paraffin torus situated in the center of a circular aperture. The receiver antenna is positioned at distance ρ. All dimensions are expressed in centimeters

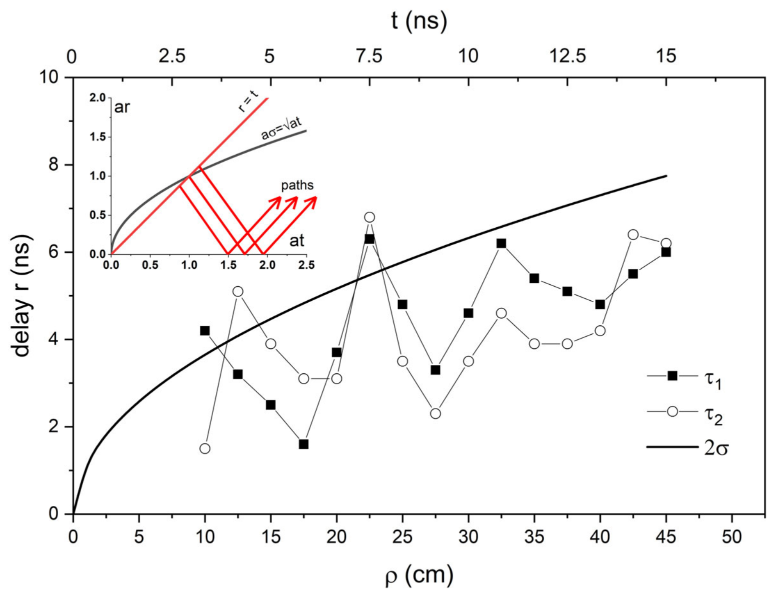

FIGURE 2 Two determinations of delay time measured as a function of the distance ρ between F_1 launcher and the receiver antenna. The heavy line represents $2\sigma(t)$ where $t = \rho/v$ is determined for $v \equiv 3$ cm/ns. Typical paths with reversals are represented in (ar, at) plane of the inset, according to Reference 21

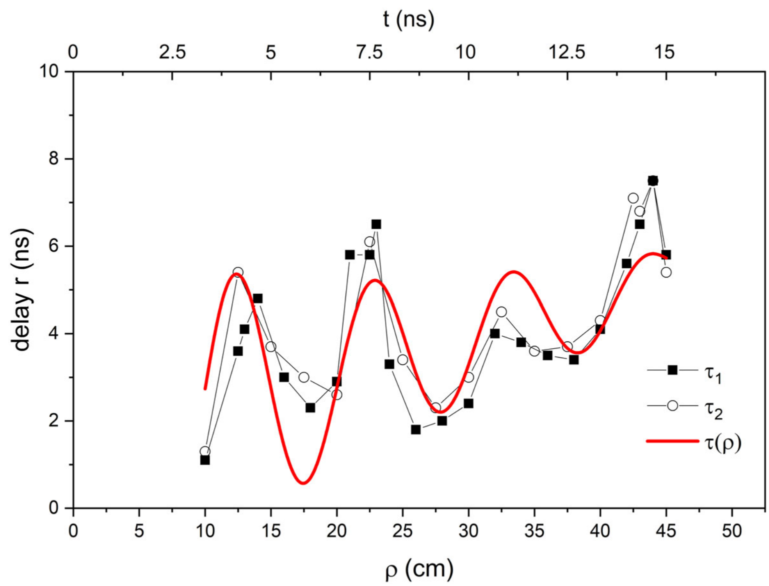

FIGURE 3 Two additional determinations of delay time measured, as a function of the distance ρ between the F_1 launcher and the receiver antenna. The continuous line was obtained by using Equation (3) for parameter values as given in the text

with a model already formulated in Reference 22, the same adopted also in Reference 4 in order to interpret the shape of the signal intensities of this system.*

According to interpretation 1, the motion is believed to happen within a two-dimensional temporal space described by a density distribution $g(r, t)$, where t is the normal time and r is a randomized time.[23] The asymptotical form of $g(r, t)$ is a Gaussian, the standard deviation of which is given simply by $\sigma = \sqrt{t/a}$, where a is the dissipative parameter entering the telegrapher's equation[24,25] (see Appendix for some analytical details).

By rewriting the standard deviation as

$$a\,\sigma = \sqrt{\frac{a}{v}\,\rho}, \tag{1}$$

where $\rho/v = t$ and v is the velocity, from the periodicity of the measured delay-time versus ρ, we find that the ratio a/v should be ~1/3. In fact, according to the stochastic model, the argument of the involved circular function is given by

*It can be easily observed that a normal interference resulting in a spatial period T of ~10 cm would require a nonplausible tilting angle δ between the F_1 and F_2 beams of about 40°, as resulting from the relation $T \equiv N\lambda = \frac{\cos\delta}{1-\cos\delta}\lambda$, where $N = 3.25$ and the microwave wavelength $\lambda = 3.2$ cm.

$2a(\rho - \rho_i)/v$. For a given spatial period T, we have $a/v = \pi/T$ which, for $T \simeq 10$ cm, gives $a/v \simeq 0.314$ cm^{-1}. In this way we can determine from Equation (1) that, for $\rho = 48$ cm, $at = 16$, hence $a\sigma = 4$. If we select the value of 10^9 s^{-1} for a (hence $v = 3$ cm/ns), we can evaluate the curve $2\sigma(t)$, as shown in Figure 2, which represents the border line of the half area that contains the paths with a probability of ~95%. The same curve represents $\sigma(t)$, if we select $a = 0.5 \times 10^9\ s^{-1}$, hence $v = 1.5$ cm/ns, and the probability will be of ~68%.

Thus, the delay-time data of Figure 2 can be reasonably considered to be representative of the hypothesized zigzag random paths. As for an estimate of the extension of $\Delta\tau$ average steps of these paths,[26] according to the Gaussian form of g(r, t), we may conclude that for $r^2 = \sigma^2 = t/a$, for $r \approx t$ we obtain $r = \Delta\tau \simeq a^{-1}$.[21] This means that in our case, for $a \simeq 0.5 \times 10^9$ s^{-1}, $\Delta\tau \simeq 2$ ns and the corresponding $\Delta\rho = v\Delta\tau \simeq 3$ cm, values which are roughly comparable with the corresponding variations in Figure 2. The involved velocity, $v = 1.5$ cm/ns, may appear to be an extremely low value, even in comparison with an average velocity of the process $\bar{v} \simeq 45/6 = 7.5$ cm/ns, which is only 1/4 of the light velocity in vacuum, $c = 30$ cm/ns. However, the above-mentioned values of v must to be comparable with the slope of the local variations in Figure 2. As disclosed above, we can assert that—according to this type of interpretation—the results shown in Figure 2 give a direct demonstration of the presence of a stochastic process in this system, as theoretically predicted in previous works. See, in particular, the shape of the paths as represented in the *ar* versus *at* plane by the inset in Figure 2 as taken from Reference 21.

On the other hand, if we adopt interpretation 2 in accordance with the model formulated in Reference 22, we would have to consider Equation (9) for the delay therein reported, which can be rewritten as

$$\frac{\tau_\varphi}{T} = \frac{d\varphi}{d(kl)} = \frac{(E_2/E_1)^2 + (E_2/E_1)\cos kl}{1 + (E_2/E_1)^2 + 2(E_2/E_1)\cos kl}, \tag{2}$$

where E_1 and E_2 are the field-amplitude relative to F_1 and F_2 beams, respectively, T is now the temporal period and kl the propagation constant. Relation (2) is the result of a vector diagram in the phase space for components E_1 and E_2 with dephasing kl. The resulting field has amplitude E and phase φ.

Under the assumption that $E_1 \gg E_2$ (in our case $E_1 \simeq 10\ E_2$), Equation (2) tends toward the simplified form $\tau_\varphi/T \simeq (E_2/E_1)\cos kl$. By assuming that in our case kl is still given by $2a(\rho - \rho_i)/v$, as previously anticipated, and by taking into account the similarity with other expressions relative to the stochastic model or to a transition-element theory (see below), we arrive at the following expression, which is suitable for describing the experimental data:

$$\tau(\rho) = A\cos[2a(\rho - \rho_i)/v]e^{-\rho/\rho_0} + B\rho + C \tag{3}$$

where $e^{-\rho/\rho_0}$ accounts for an evident attenuation of the oscillation amplitude and the second term for a linear increase in the average delay time. The resulting curve, obtained for $A = 5$ ns, $a/v = 0.3\ cm^{-1}$, $\rho_i = 12.4$ cm, $\rho_0 = 25$ cm, $B = 0.08$ ns/cm, and $C = 1.5$ ns as an acceptable offset of the data, is depicted in Figure 3 and represents a rough but plausible description of the experimental results, there reported.

4 | DISCUSSION AND CONCLUDING REMARKS

We can therefore conclude that this latter hybrid model (Equation 3) seems to be capable of interpreting the anomalous transfer of modulation observed between the two microwave beams. Of particular interest is the fact that the observed behavior of delay time in the transferred signal is far from the observed behavior of the near field emerging from the composed pupil, which shows a marked superluminal feature.[27] In the present case, although the involved mechanism is essentially the same, that is, a stochastic model, the obtained results demonstrate a sub-luminal behavior.

However, at present, as discussed in Reference 4, we have no sufficiently conclusive theoretical arguments for supporting the above conclusion. One considered possibility is that the transfer of energy from F_2 to F_1 beam is due to a photon-photon scattering mechanism occurring in the crossing area. This hypothesis could be justified by the fact that the photon rest mass is not exactly zero,[28] but it is practically so.[29]

Another plausible interpretation of the effect observed could be due to a mechanism of a local breaking of the Lorentz invariance as invoked for an alternative interpretation of superluminal behavior in systems of this kind:[30,31] an alternative with respect to more canonical electromagnetic interpretations.[32]

However, the presence of a virtual nonlinear medium previously invoked as being in the crossing area of the two beams[1,3] is now not yet required being merely represented by the detector following the receiver antenna, the characteristic of which is an almost quadratic one.[4]

Further experimental work is planned in order to discriminate between the proposed models, although a hybrid mixing, between interpretations 1 and 2 in Section 3, is likely to be the most plausible.

In this perspective, it is useful to recall that situations of wave propagation of a single beam in presence of solid supports (such as dielectrics or metals), including or not the contribution of losses, were previously analyzed in Reference 22. The present case does not fall within those cited in Reference 22 because it occurs in "free space."

Moreover, we have to mention that scaling the carrier frequency from ~10 GHz to 1–2 GHz, as well as increasing the spatial separation to some meters,[33] did not produce any substantial change in the delay measurement, relative to a single beam employing a suitable horn antennas (mouth sizes $76 \times 59\ cm^2$), other data can be found in Reference 34 for other results. On the other hand, when the horn antennas were substituted by ten-turns helical ones, operating in the same frequency range $(1-2)$ GHz, the superluminal behavior previously obtained was not confirmed.

PEER REVIEW INFORMATION

Engineering Reports thanks Saptarshi Mukherjee and other anonymous reviewers for their contribution to the peer review of this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

CONFLICT OF INTEREST

The authors have no conflict of interest relevant to this article.

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How to cite this article: Cacciari I, Mugnai D, Ranfagni A. Delay time in the transfer of modulation between microwave beams. *Engineering Reports*. 2021;e12392. https://doi.org/10.1002/eng2.12392

APPENDIX A. SOME ANALYTICAL DETAILS

According to Reference 23, the solution to the telegrapher's equation can be expressed by a quadrature in which the two-variable function $g(r, t)$ enters the integrand. This function is the density distribution of a randomized time r, while t is the normal time, and tends asymptotically, for $t \gg r$, to a Gaussian

$$g(r,t) \simeq \sqrt{\frac{a}{2\pi t}} \exp\left(\frac{-ar^2}{2t}\right), \tag{A1}$$

where a, as stated above, is the dissipative parameter entering the wave equation. The standard deviation of (A1) is given by $\sigma = \sqrt{t/a}$. More exactly, $g(r, t)$ is given by two Gaussians with half amplitude of (A1), one centered at $r = 0$, the other at $r = 1/a$, in accordance with the fact that the average values of r is given by[25]

$$\langle r \rangle = \frac{1}{2a}(1 - e^{-2aL/v}), \tag{A2}$$

L being the traveled distance and v the velocity.

In some situations, such as the present case of near-field propagation, we observe an inversion of roles between r and t, in the sense that r becomes the observable quantity.[†]In particular, in classically forbidden processes (tunneling), by operating an analytical continuation to imaginary time,[35] we have that the delay (or traversal) time becomes a complex quantity, the real part of which is given by[36]

[†]This can be interpreted according to weak-measurement theory as done in the case of Reference 27.

$$\Re\langle t\rangle = \frac{1}{2a}[1 - \cos(2aL/v)]. \tag{A3}$$

As an alternative to the stochastic model, we can adopt another approach to this kind of problem, one based on the transition-elements by Feynman.[11] In this case, we obtain that the real part of the traversal time is given by[37]

$$\Re\langle t\rangle \simeq \frac{L}{v}[1 - A\cos(2aL/v)]e^{-\alpha L}, \tag{A4}$$

where $A \simeq a/2\omega$, ω being the circular frequency and α being the attenuation constant. Before being adopted for the purpose of describing the experimental data of delay time, the form of Equation (3), is substantially identical to this last Equation (A4).