Anomalous pulse delay in microwave propagation: A case of superluminal behavior

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Delay time measurements of microwave pulses, in open air propagation, have been repeated by using horn antennas in the near-field region at different frequencies. The delay decreases when the receiver is shifted or tilted with respect to the launcher showing superluminal behavior which disappears for distances beyond the near-field limit. These results are interpreted by a model where complex waves—a special kind of decaying wave—are dominant. [S1063-651X(96)03310-7]

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I. INTRODUCTION

Much experimental evidence of superluminal behavior, that is, motions faster than the speed of light, is now available, however, at present, it is not fully understood whether these results hold good for a *true* signal or not [1]. All the cases are concerned with tunneling processes, more exactly with optical tunneling. In the visible region, the obtaining of superluminal effects requires an investigation in the time scale of femtoseconds (the distances are of the order of microns) [2,3]. With microwaves, we can have such effects in the time scale of nanoseconds (the distances are of the order of tens of cm) with a magnification (gain) of 5–6 orders of magnitude [4]. This possibility is explained by considering that such an effect is connected with evanescent waves which decay over the distances of only a few wavelengths. A special kind of decaying waves are the proper complex

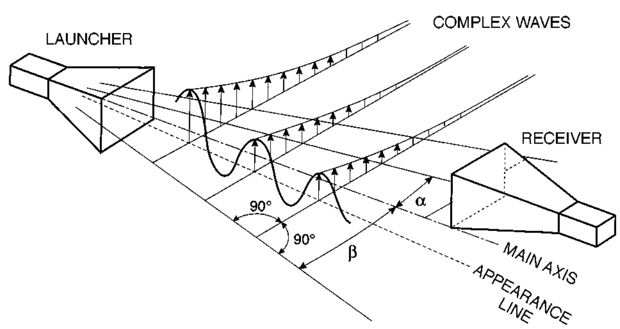

FIG. 1. Microwave propagation experiment with horn antennas. A special kind of decaying waves, the complex waves, are operating at moderate distances from the launcher and can be detected by the receiver in a selected range of the values of angle α. The complex wave fronts are perpendicular to a plane roughly coincident with the vertical plane of the launcher horn, forming the angle β with the axis of the horn. When the receiver horn is displaced, the sum of the angles $\alpha+\beta$ increases and the observed pulse delay decreases according to Eq. (3). Angle β is a complex quantity. When the real part (β_r) is comparable to the imaginary one (β_i), the appearance line of the complex waves is situated near the main axis ($\alpha=0$). Only the complex waves attenuating on the left side of the launcher are represented here; there are, of course, also complex waves attenuating towards the right corresponding to another pole situated at $-\beta$.

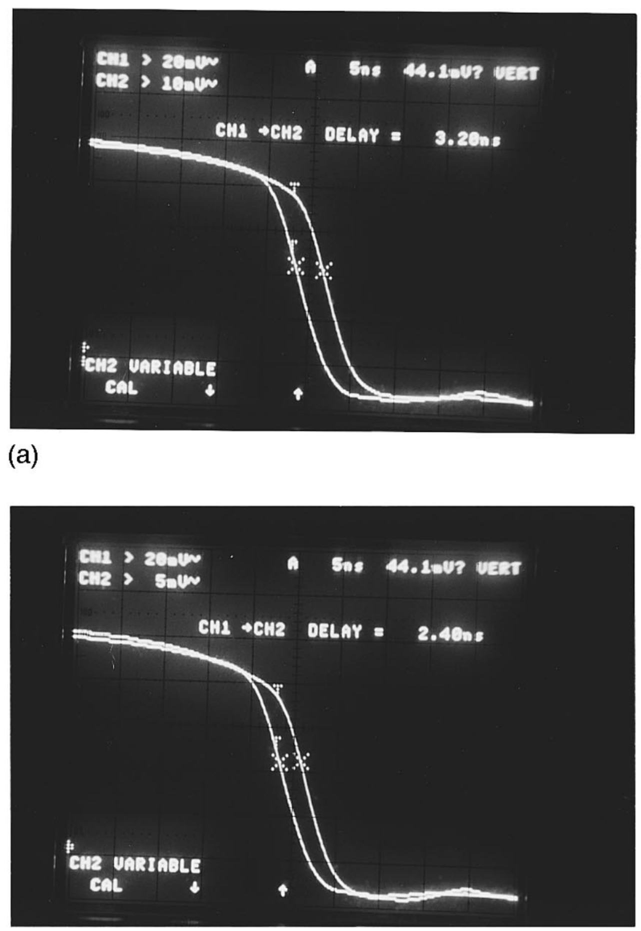

FIG. 2. Demonstration of the attainment of the superluminal behavior at 9.5 GHz. The photos show the detected envelope of the pulse modulated signals taken before the launcher and after the receiver at two points separated by a distance of about 90 cm. Case (a): the antennas are facing each other, and the distance between the mouths is $L=53$ cm. The delay of 3.2 ns is in agreement with a propagation velocity equal to c. Case (b): the receiver is displaced perpendicularly by an amount $l=16$ cm. The delay of 2.4 ns corresponds to an average velocity equal to 1.25 c, but the velocity in the open-air path rises to about $2c$. The falling edge of the pulse was chosen because it was considerably shorter (≈ 5 ns) and cleaner than the rising edge (≈ 30 ns).

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TABLE I. Near-field limit $R=2D^2/\lambda$, where D is the width of the antenna aperture and λ the wavelength.

ν (GHz)	λ (cm)	$R(D=76$ cm$)$ (cm)	$R(D\simeq 11$ cm$)$ (cm)
1.2	25	462	
1.5	20	578	
2	15	770	
10	3		81

waves [5], which can be particularly persistent and can be detected, for microwaves in the X band ($\lambda\sim 3$ cm) up to distances of the order of one meter [6] and even more if the wavelength is increased up to tens of cm. We can thus have a further amplification of the effect, and this is exactly what we have done in our experiments. The results obtained are discussed here in the attempt to give a satisfactory answer to the question of the velocity of a signal.

II. EXPERIMENT

The experiment in the X band consisted of an ''open-air'' pulse transmission with two small horn antennas (mouth sizes 13.5×10.5 cm^2 and 9×8 cm^2, flare angle 40°–50°) over a distance less than one meter (see Fig. 1). A microwave signal similar to a step function was supplied by a generator, at a frequency $\nu_0\simeq$ 9.5 GHz, modulated by a pin modulator whose fall time, less than 10 ns, was suitable for measuring delay times down to less than 1 ns [7]. The signals taken at the launcher and at the receiver (the spatial separation is $\sim$90 cm) were sent to a high-temporal-resolution oscilloscope that was able to measure the delay with an accuracy of $\pm$ 0.1 ns (see Fig. 2). Initially, the launcher and receiver horns were facing each other, separated by a distance $L=53$ cm. In this condition, we measured a pulse delay (3.2 ns) corresponding to a propagation velocity nearly coincident with the light speed c, as expected. Then the receiver horn was shifted transversely. With an increase in the perpendicular displacement l, the measured delay constantly *decreased* (see also Fig. 6). When $l=16$ cm, the pulse delay was shortened by 0.8 ns and the average propagation velocity was equal to 1.25 c. However, considering that the delay in the two horns was presumably constant, the actual velocity in the free space would be near twice the light speed. This behavior was confirmed also for different values of L but, for distances greather than about one meter, that is beyond the near-field limit (see Table I), the effect becomes unobservable [6].

Further investigations have been carried out, in the range of frequency between 1 and 2 GHz, by employing two big horn antennas (mouth sizes 76×59 cm^2, flare angle $\sim$30°) designed for operating at 1.2 GHz. Results of delay time obtained as a function of the tilting angle α of the launcher are shown in Fig. 3 where the ratio $\tau(\alpha=0)/\tau(\alpha)$ is reported. In such a way we obtain the signal velocity (v_s)

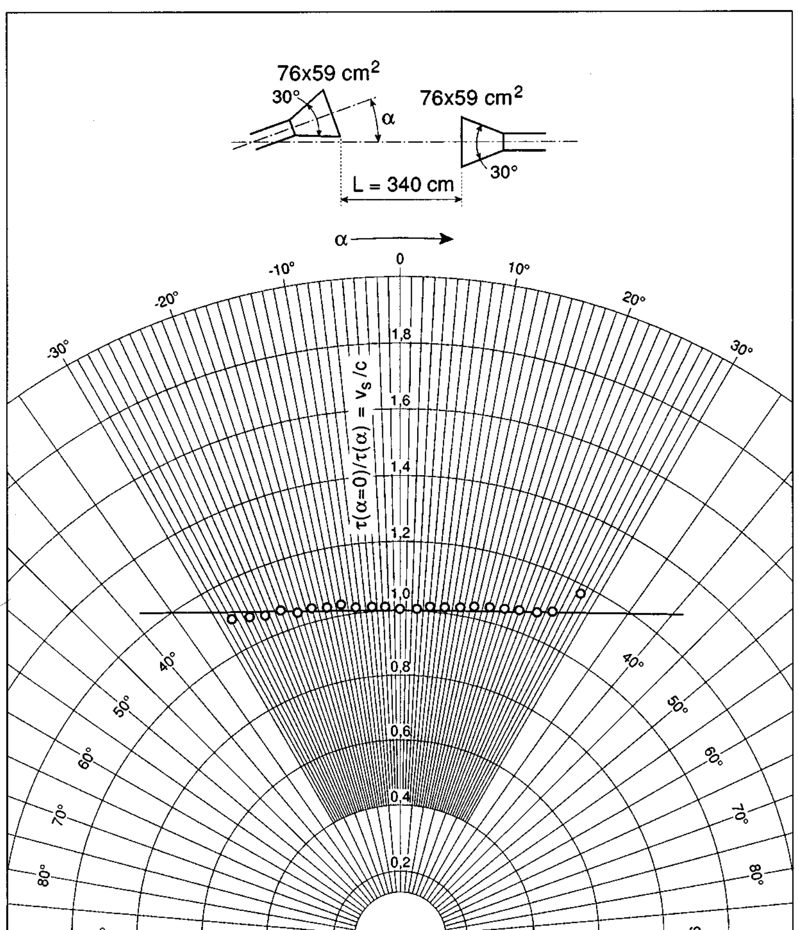

FIG. 3. Ratio of the pulse delay at 1.2 GHz for $\alpha=0$ to that for α variable as a function of the tilting angle α for a distance $L=340$ cm between the mouths of the two horns. The experimental points are fitted by a straight line corresponding to Eq. (3) with $\beta_r\simeq\beta_i\simeq 0$.

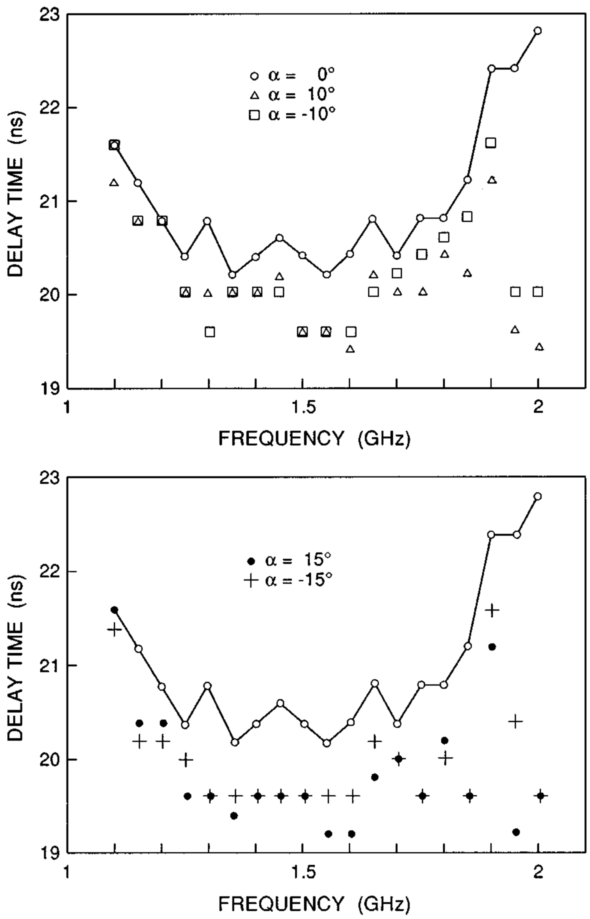

FIG. 4. Pulse delay in propagation experiments with two horns, as in Fig. 3, as function of the frequency in the interval 1.1–2 GHz, measured at fixed values of the observation angle α. The signals were taken at the launcher and at the receiver, with a spatial separation of $\sim$7 m (the distance between the antenna mouths was $L=338$ cm). The shortening of the pulse delay tends to increase with frequency in agreement with the increasing of the near-field limit, see Table I.

relative to the velocity for $\alpha=0$, assumed to be coincident with the light speed c. We note that for the considered distance between the horn mouths, $L=340$ cm, the ratio v_s/c increases by increasing the tilting angle α. By increasing the distance L, the effect tends to disappear, for instance, for $L=585$ cm the ratio v_s/c is found to be constantly equal to the unity in the same interval of α values. Delay time measurements have been made, for fixed values of α, as function of the frequency. The results reported in Fig. 4, for $L=338$ cm, confirm the previous ones. We note also a tendency to increase the effect (shortening of the delay for $\alpha\neq 0$) with increasing frequency. This agrees with the fact that the limit of the near field, accordingly to its conventional definition [8], constantly increases with the frequency, see Table I.

III. THEORETICAL INTERPRETATION

The above results can be interpreted in the following way. Let us assume that the radiated field from the launcher, given by a superposition of plane waves, can be expressed as that of a rectangular aperture—the mouth of the horn—in the scalar approximation. Under these assumptions the field distribution is described by a contour integral in the complex plane of z angle

$$\int_c A(z)\exp[ik\rho\cos(z-\alpha)]dz, \tag{1}$$

where $A(z)$ is the amplitude, ρ and α the polar coordinates of the observation point, and $k=2\pi/\lambda$ is the wave number. This integral (1) can give rise to a pole contribution (complex wave) whose origin is demonstrated in the Appendix of Ref. [6] in the framework of the Fresnel, or near-field, region. Really, we have a couple of $\pm\beta$ complex poles which can contribute or not to the radiated field, depending on the observation angle α, if the steepest-descent path in the integral (1) captures both poles, or only one of them, or no one [5,6,8].

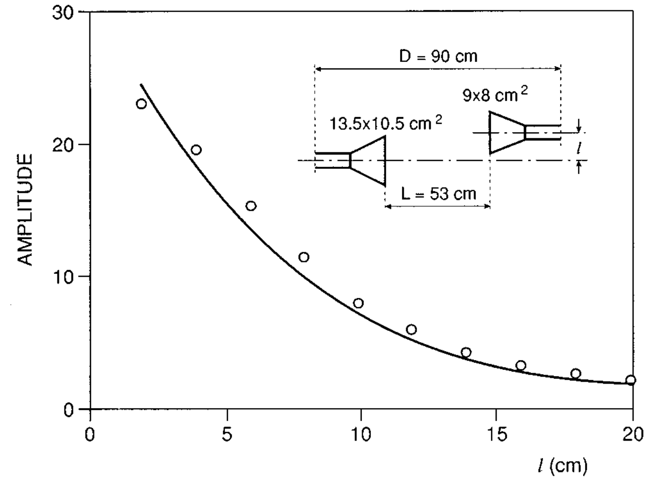

FIG. 5. Measured amplitude of the field (arbitrary units) at 9.5 GHz as a function of the perpendicular displacement l, for $L=53$ cm. The continuous line is a fit of Eq. (4) obtained for $A_0=766$, $\beta_r=20°$, $\beta_i=5°$. The total distance between the two detection points is about 90 cm.

Since for long distances (say beyond the near-field limit) the shortening of the decay time disappears, let us assume that in the region of our interest (that comprised between the two horn antennas) the radiated field is mainly constituted by complex waves. This assumption is certainly a crude approximation, but it is qualitatively correct since, under particular conditions ($\beta_i\rightarrow 0$ or $\alpha\rightarrow-\beta_r$), the complex waves can be relatively little attenuated and can prevail over the ''normal field'' contribution which decays as the inverse of the distance. According to the analysis of Ref. [9], this field can be expressed, in polar coordinates, as $\sim 2\pi i\exp[ik\rho\cos(\beta+\alpha)]$ where $k=2\pi/\lambda$, ρ is the distance, α the angle of observation and $\beta=\beta_r+i\beta_i$ a complex angle (pole position). Accordingly, the amplitude decays as

$$A\propto\exp\left[-\frac{2\pi\rho}{\lambda}\sin(\beta_r+\alpha)\sinh\beta_i\right], \tag{2}$$

and the phase time delay is given by

$$\tau-\tau_0=\frac{\rho}{v_{pp}}=\frac{\rho}{c}\cos(\beta_r+\alpha)\cosh\beta_i, \tag{3}$$

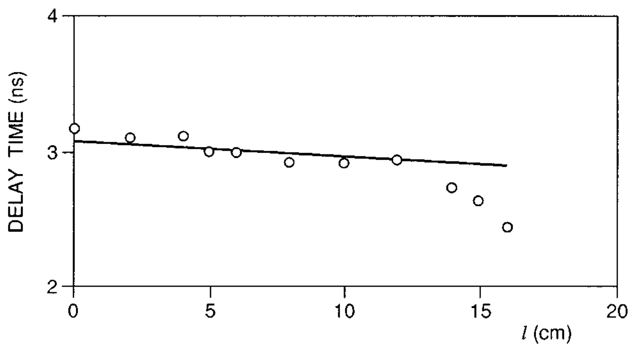

FIG. 6. Measured pulse delay as a function of the perpendicular displacement l at 9.5 GHz. The straight line is the fit of Eq. (5) again calculated for $\beta_r = 20°$, $\beta_i = 5°$, and obtaining $\tau_0 = 1.41$ ns.

where τ_0 is the delay in the two horn antennas, $\rho = \sqrt{L^2 + l^2}$ is the distance between the mouths of the horns, v_{pp} is the phase-path velocity along the path with angle α (see Fig. 1), β_r is roughly comparable to one half of the flare angle of the launcher and β_i is related to the attenuation of the complex wave. We wish to note that, in a nondispersive situation like that of the present experiment, the phase-path velocity is coincident with the group-path velocity and, presumably, also with the signal-path velocity (Sec. IV). Equations (2) and (3) can be rewritten in orthogonal coordinates as follows: ($L \equiv x = \rho \cos\alpha$, $l \equiv y = \rho \sin\alpha$)

$$A = A_0 \exp\left[-\frac{2\pi}{\lambda}(L \sin\beta_r + l \cos\beta_r)\sinh\beta_i \right], \tag{4}$$

$$\tau = \tau_0 + \frac{(L \cos\beta_r - l \sin\beta_r)\cosh\beta_i}{c}. \tag{5}$$

The continuous line in Figs. 5 and 6 is a fit of the experimental results of the X-band experiment obtained, for $L = 53$ cm, with $\beta_r = 20°$, $\beta_i = 5°$, $A_0 = 766$ and $\tau_0 = 1.41$ ns. This corresponds to a propagation velocity equal to 1.25 c, for $l = 16$ cm. So, we arrive at the conclusion that the ''anomalous'' pulse delay is nothing but the effect of a special kind of decaying waves in the near field radiated by horn antennas. The shortening of the delay of the signal is due to the inclination of the observation path, the angle $\alpha + \beta_r$ in Fig. 1, with respect to the direction of β_r. The angle α cannot be augmented much beyond the opposite side ($-\beta_r$): that is, the maximum of the path slope is comparable to the flare angle ($\approx 2\beta_r$) of the launcher, where we observe an increase of the order of 20–30 % in the signal velocity. If we could further increase the inclination, we would certainly obtain faster and faster propagation velocity, which tends to infinity for paths tending to be coincident with the wave front. In this way, we reobtain a situation that is almost analogous to that of the subcutoff waveguide where evanescent waves are operating [4,10].

IV. CONCLUSION

Anomalous pulse delay in microwave propagation experiments has already been observed [11] and attributed to the increasing of the *phase velocity*, both in open-air transmission and waveguide propagation. In the latter case the experiment of Ref. [11] does not refer to a subcutoff situation, but rather to a ''normal'' overcutoff propagation. While the present results confirm such a conclusion for the open-air transmission (absence of dispersion), our measurements do not confirm the results relative to the normal wave guide propagation in which, as expected, the signal velocity is coincident with the group velocity (less than c) [6,12].

The only surviving case, in addition to the subcutoff waveguide experiment [4,10], is the open-air propagation with horn antennas which here has been interpreted on the basis of the complex waves. In both cases, the superluminal effect is attributed to decaying waves.

It remains to answer the question posed at the beginning, as to whether these conclusions hold good for a *true signal* or not [13]. In other words, can evanescent waves carry information? Very recently we have demonstrated [14] that, in the case of evanescent waves, by limiting the spectral extension we can actually obtain the arrival of something before the usual forerunner for time less than ρ/c. As is known, a finite spectral extension cannot represent a true signal which, on the contrary, would require an infinitely extended spectrum. In the case of optical tunneling (visible region or microwaves) the choice to limit the frequency domain is supported by the fact that evanescent waves do have a finite spectral extension [15]. In this case, the necessary adoption of spectral limitations allows for the theoretical obtainment of superluminal effects that are observable with ''signals'' that are sometimes referred to as ''technical signals'' propagating with ''technical information velocity'' [16,17]. The results presented here, although not referred to proper evanescent waves, strongly support this point of view.

ACKNOWLEDGMENTS

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receiver was appreciably shorter than the trasmitted one, analogously to what is observed in Ref. [3]. This feature (presumably caused by a modification of the spectrum due to the amplitude dependence of the complex waves, which vary exponentially with frequency) gave rise to an enhancement of the effect if the delay measurements were made on the fall edge of the pulse, while the effect was attenuated (or disappeared) if the measurements were made on the rising edge of the pulse. These measurements were, however, less reliable since the rise time was six times greater than the fall time.

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