Observation of Superluminal Behaviors in Wave Propagation

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The possibility of observing superluminal behavior in the propagation of localized microwaves over distances of tens of wavelengths is experimentally demonstrated. These types of waves, better than the evanescent modes of tunneling, can contribute to answering the question on the luminal limit of the signal velocity.

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The principle that no signal can travel faster than the light speed in vacuum is accepted as one of the basic laws of nature [1]. Yet, there is no formal proof, based only on Maxwell's equations, that no electromagnetic wave packet can travel faster than the speed of light. Therefore, there may be a shadow of doubt as to whether this principle is true in any case [2]. However, the question as to whether a wave packet can be considered a signal is a much debated and complicated one [3–6]. Superluminal effects for evanescent waves have been demonstrated in tunneling experiments in both the optical domain and the microwave range [7–12]. What clearly emerges from these works is that the delay time in crossing a barrier, the width of which is comparable to the wavelength, is considerably shorter than the time employed by traveling at the speed of light in vacuum. This implies, however, that such an effect can be revealed only over short distances—the limitation being due to the evanescent field—which for microwaves (the more favorable case) are of a few centimeters. The question as to whether it is possible to extend this effect over larger distances, apart from the obvious consequence of increasing the wavelength, naturally arises. The purpose of this paper is to demonstrate such a possibility in the propagation of localized microwaves over distances of some tens of wavelengths, that is, of the order of 1 m or more, and to contribute to answering the above question on signal velocity.

Experimental evidence of localized light waves in a centimeter range (an appreciable one in view of the smallness of the optical wavelength) has recently been given [13], demonstrating a practical way of obtaining these types of waves (X shaped). These waves, in fact, have been theoretically predicted and investigated as Bessel beams since the 1980's [14,15], and even before that date for their directivity properties [16], and then in connection with their superluminal behavior [17,18]. The latter derives from a $\cos\theta$ dependence, where θ is the cone angle of the Bessel beam. We have extended the experiment of Refs. [13,14] in the microwave range, obtaining a magnification of the effect (but a reduction in the relative field depth) by adopting θ angles of the order of 0.3–0.4 rad. In the optical experiments, instead, this angle is typically of the order of 10^{-2} rad, which prevents the direct observation of superluminal effects. The field of a Bessel beam is described by the axisymmetric (φ invariant) expression, which represents diffraction- and (dispersion-)free mode solutions,

$$J_0(\rho k \sin\theta) \exp[i(zk \cos\theta - \omega t)] . \qquad (1)$$

Here, J_0 is the zeroth-order Bessel function of the first kind, ρ is the transversal distance from the propagation axis z, $k = \omega/c$ is the wave number, and the parameter θ is the cone angle of the Bessel beam which has a top angle 2θ [13,14]. According to expression (1), the field can be considered as built up as the superposition of pairs of plane waves, the direction angles of which are (θ, φ) and $(\theta, \varphi + \pi)$, i.e., X waves, that move along the z axis with speed $v = c/\cos\theta$ that is both the phase and the group velocity (when several k are considered) of the wave field in the direction of the z axis. Clearly, $v > c$, and the effect is more or less pronounced, depending on the θ angle. A beam having the characteristics of expression (1) can be created, in practice, by a circular slit placed in the focal plane of a lens [13,14] or, as in our case, of a mirror. Ideally, each point along the slit acts as a point source which the converging device (lens or mirror) transforms into a plane wave tilted over the z axis by the angle $\theta = \tan^{-1}(d/2f)$, d and f being the mean diameter of the slit and the focal length, respectively.

Figure 1 shows the experimental setup that we adopted for our measurements at microwave scale ($\lambda \simeq 3.5$ cm). The circular slit, with a mean diameter of 7 or 10 cm, is fed by a horn antenna (the launcher) connected to the microwave generator through a waveguide, and placed in the focal plane of a spherical mirror, the diameter of which is $2R = 50$ cm and the focal length $f = 12$ cm. In this way, we operate with θ angles of $\sim 16°$ or $\sim 23°$ which should produce an increase in the velocity of 4% and 8%, respectively. These variations were expected to be easily detectable, even if the field depth of the Bessel beam, given by $R/\tan\theta = 2Rf/d$ turned out to be only 86 or 60 cm, respectively. These situations were completely different from the optical experiments, where θ was less than 1° and the field depth was about 1m (a considerable one, given the smallness of the wavelength), but the superluminality was unobservable. A second horn antenna, placed on the z axis at the distance L from the focal plane,

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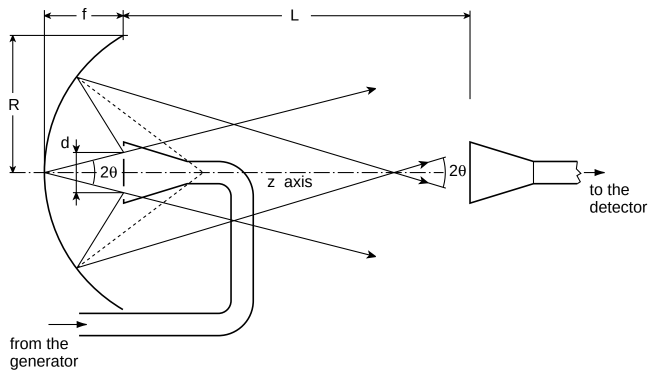

FIG. 1. The experimental setup for microwave measurements consists of a circular slit with mean diameter d, fed by a horn antenna (launcher) placed in the focal plane of a circular mirror with radius R and focal length f, and of a second horn antenna (receiver) placed at a variable distance L on the z axis.

acted as a receiver and was connected to the detector. The microwave carrier ($\nu \simeq 8.6$ GHz) was modulated by rectangular pulses, with rise and fall times of a few nanoseconds. The modulation was detected, before the launcher and after the receiver, and the signals were sent to a two-channel digital real time oscilloscope (Tektronix TDS 680B), where the delay time between the two pulses was measured with a sensitivity of the order of 10 ps. The results reported in Fig. 2 (filled circles) were obtained by measuring the delay time as a function of the distance L, in the 30–130 cm range, with a circular slit whose diameter was ~7 cm ($\theta \simeq 16°$). Note that there is an offset of about 5 ns in the time scale, the delay relative to $L = 30$ cm being about 1 ns.

These data can be reasonably fitted by a straight line, the slope of which gives the inverse of the mean velocity. From each pair of delay data, we evaluated the punctual velocity as $\Delta L/\Delta T$: the results obtained are shown in the upper part of Fig. 2, with their fiducial bars calculated as $\delta(\Delta T)\Delta L/(\Delta T)^2$ assuming $\delta(\Delta T) \simeq 30$ ps. We note that, although each one is affected by a non-negligible error, the velocity results tend to be placed appreciably above the horizontal line of $v \equiv c = 30$ cm/ns. A more quantitative result was obtained by the linear fit of the delay data. From this fit, we deduce that the delay over one meter is 3.155 ns, the ratio of which to 3.333 ns (the delay at light velocity) gives 0.947, with a precision of 1.3%. The fit of a second series of measurements (not shown in Fig. 2) is represented by other parameter values: from these values, we obtain 3.093 ns for one meter, which gives a delay ratio of 0.928 with an accuracy of 1.5%. The coefficient of determination (or, more properly, the correlation coefficient [19]) of these fits is $r = 0.99931$ for the case of Fig. 2, and $r = 0.99838$ for the second series of measurements: these values, very close to the unity (the maximum value of r), represent very good fits. Therefore, within the errors, these results confirm each other, although the percentage of superluminality (5.3%–7.2%) is slightly greater

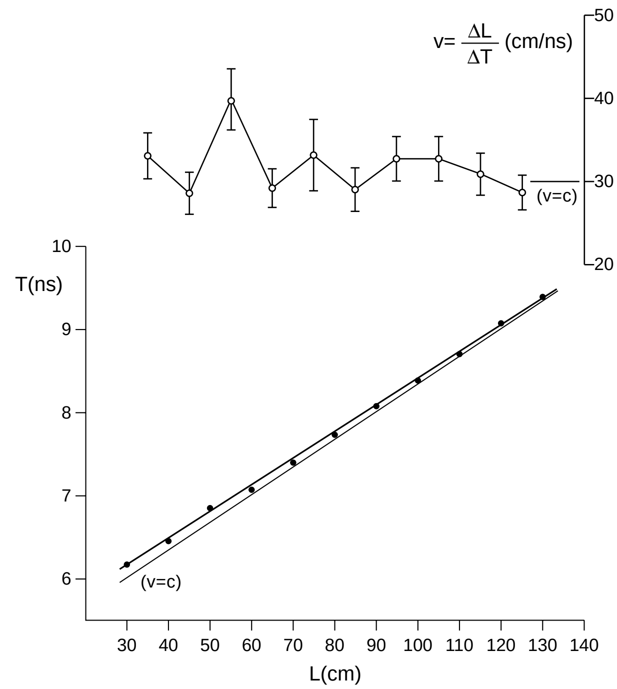

FIG. 2. Delay time measurements (filled circles) as a function of distance L for a slit diameter $d \simeq 7$ cm. The heavy continuous curve is a linear fit, with a slope less than the straight line $v = c$. Velocity results (open circles with fiducial bars) reported in the upper part indicate a slight superluminal behavior (the mean velocity is appreciably greater than the light velocity by 5.3%) even if it tends to disappear for $L > 1$ m.

than the predicted one which, as previously anticipated, should have been about 4%.

In order to obtain a more evident result in the superluminality, we performed some measurements with a circular slit of ~10 cm in diameter ($\theta \simeq 23°$). The measured delay as a function of distance L, in the 40–140 cm range, is reported in Fig. 3 (filled circles). In this case, there is an offset in the time scale of about 6 ns. These results cannot be fitted, even roughly, by a straight line. For an L greater than ~1 m, the behavior is practically coincident with the straight line $v = c$, while the deviation is more and more evident for the smaller distances and a good description ($r = 0.99955$) was obtained by a second order polynomial. In the upper part of Fig. 3, we report the velocity results obtained as before with their fiducial bars, while the continuous curve was obtained as the inverse of the derivative of the fitting polynomial of the delay data. We note that, although the velocity results are affected by errors which strongly increase at the lower values of L, the overall curve shows a clear superluminal behavior, provided that the distance is within 1 m (the mean effect over this distance is about 25%, even if less pronounced effects were also obtained in other measurements). This behavior exceeds the one predicted for the Bessel beam: about 8% on the basis of the simple geometrical model before being adopted, and a field depth of less than 1 m.

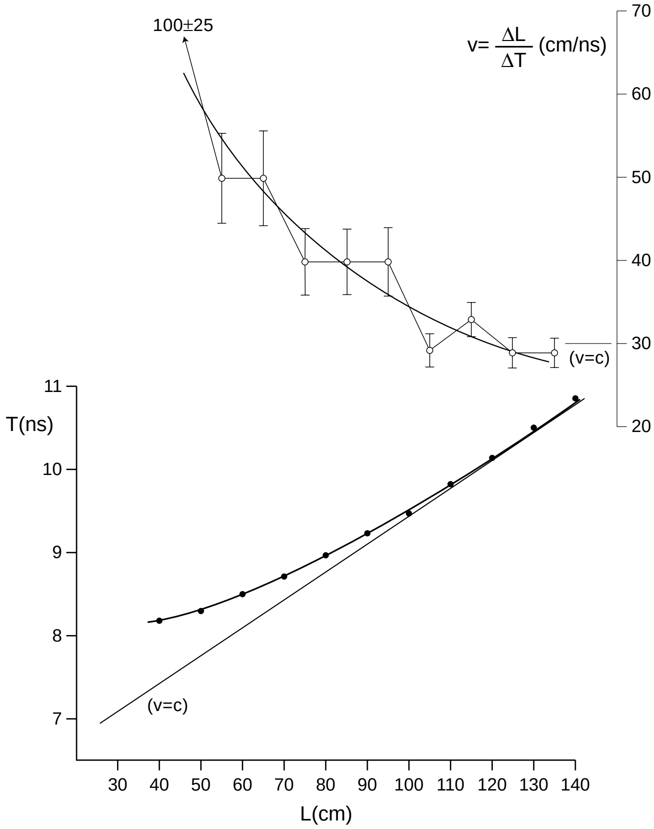

FIG. 3. Same as Fig. 2 for a slit diameter $d \simeq 10$ cm. The heavy continuous curve is a polynomial fit. The velocity results, as deduced from delay data or from the inverse of the derivative of the fitting curve, show a marked superluminality for $L < 1$ m.

The reasons for this enhancement are not completely clear. One cause can be identified by considering that, at lower L distances, the aberration of the mirror will favor a more pronounced inclination of the rays (say, $\theta \approx 30°$) originating from the external region of the mirror (the central region being shielded by the launcher horn). This, although increasing the expected effect to about 14%, is not sufficient to explain the strong observed one; other reasons, to be found in a Fresnel-optics framework (not merely a geometrical optics), are likely to be considered, since we are in fact in near-field situations. We can mention two facts in favor of this hypothesis:

(i) In the optical experiment of Ref. [14] the peak intensity of the Bessel beam is reminiscent of the Fresnel diffraction pattern close to a knife edge. However, it is important to note that such behavior represents the intensity away from the aperture (the lens) up to a distance of about 1 m, rather than diffraction in the transverse plane near the aperture.

(ii) In a microwave propagation experiment with two horn antennas [20], a shortening of the pulse delay was observed when the receiver horn was shifted with respect to the launcher horn by an amount of 20–25 cm, taking distance L at a fixed value. For $L \gtrsim 1$ m, this effect is negligible, while it becomes more and more evident, up to about a reduction of 100%, when $L = 21$ cm.

This behavior was interpreted on the basis of a complex wave analysis, which leads to a $\cos(\beta - \alpha)$ dependence, where α is the angle of observation and β is the angular coordinate of a pole singularity [21]. Therefore, also this model is reminiscent of the present one. Again, however, there is a strong difference since in the case of Ref. [20] the axial symmetry was perpendicular to the z axis, while in the present experiment we observed a superluminal effect going away from the aperture (the mirror), rather than translating perpendicularly and producing an effect which could be considered as a marginal one. As for the limited field depth of the present experiments (less than 1 m, comparable with that of the optical experiments), it could be augmented by reducing the θ angle. We adopted θ values as large as possible, in order to obtain clear evidence of superluminality. Of course, by reducing θ down to the values of the optical experiments ($\theta \approx 1°$) we could obtain a field depth of some tens of meters; but the superluminal effect should have been practically unobservable, as in the optical experiments. Although strongly increasing the one accessible in tunneling experiments, this range is not very significant in a telecommunications context, even if it can be extended to any distance whatsoever by appropriately augmenting the aperture (or antenna dimensions) and reducing the θ angle [22]. More important is the significance of the present results to fundamental physics.

Turning back to the question put at the beginning, regarding the meaning to be attributed to the demonstrated superluminality, we recall that there are at least two ways of considering this meaning, which lead again to Ref. [5] or Ref. [6], respectively. The superluminality in tunneling processes is, in the case of Ref. [5], confined only in the domain of group velocity, which can never be extended to the signal velocity, while the point of view of Ref. [6] is more disposed in this respect. A crucial role is played by the spectral extension of any physical signal. In fact, by following Brillouin [1] we find that the propagation of a pulse (a single event) can be described by a contour integral in the complex plane of the ω frequencies. By extending the integration domain to infinity, we find that the first forerunner of the signal cannot arrive before a time given by L/c. If, however, we limit the range of integration, that is, by considering a finite spectral extension of the signal, the result can actually be that something arrives before the usual forerunner at a time t, so that $0 \leq t \leq L/c$ and for short distances [23].

We are aware that a finite spectral extension does not constitute a true signal (according to Brillouin) which, on the contrary, requires an infinite spectrum. We note, however, that any practical signal necessarily has *finite* spectral extension. The relative delay time, sometimes referred to as *technical signal* or *technical information* delay [24], does not necessarily coincide with the front-edge delay, which requires considering the limit $\omega \rightarrow \infty$. This is a delicate point, since infinite frequencies do not exist in physical phenomena [25] and, in practical applications such as telecommunications, radar, etc., where there is no question of propagation velocity, information travels over finite (narrow) frequency channels.

The absence of dispersion (which, on the contrary, is always present in tunneling systems) as in the case considered here, strongly simplifies the problem. In fact, we find that all of the components in the spectral extension (due to a modulation of the carrier) have the *same* propagation velocity, $v = c/\cos\theta$. This implies that the wave packets are not deformed while propagating, without the so-called "pulse reshaping" which is more or less always present in tunneling processes. Some caution is required, however, since the wave solutions (1) are rigorously exact only in infinite free space, whereas any realization of these beams will necessarily be limited by a finite aperture [14]. Thus, as noted in Ref. [16], the intrinsic limitations of these techniques imply a reduction, not an elimination, of diffractive spreading. In spite of this, the waves tested here, which are genuine superluminal solutions of the Maxwell equations [22], in addition to and better than the evanescent modes of tunneling, represent promising candidates for providing an answer to the question raised at the beginning regarding the existence of cases in which this principle does not hold true.

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