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Article *in* Modern Physics Letters B · November 2011
DOI: 10.1142/S0217984905009274

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MODERN PHYSICS LETTERS B

Volume 19, Number 27
November 30, 2005

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Modern Physics Letters B, Vol. 19, No. 27 (2005) 1403–1410

UNEXPECTED BEHAVIOR IN THE CROSSING OF MICROWAVE AND OPTICAL BEAMS

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Received 7 March 2005

The question of the superluminal speed of information was stopped at crossroads in the last few years. According to one point of view, this speed must be limited to the light velocity in vacuum, whereas a different point of view is more open in this respect and, under specific conditions, this limit is considered surmountable. Very recently, a third approach (based on the hypothesis of a local broken Lorentz-invariance) was proposed and, if confirmed, would go beyond the controversy of the two points of view mentioned above. It is therefore worthwhile to recall attention to this problem, which is far from having a definite solution. The present paper reports some experimental results (similar to those of Ref. 1) which can contribute to these discussions, and also considers the fact that they seem to give some support to the aforesaid third approach, although revised in terms of decaying waves.

Keywords: Electromagnetic propagation experiments; optics and microwave; complex waves; superluminality; Lorentz invariance.

PACS Number(s): 41.20.Jb, 03.65.Sq, 03.30.+p

In a previous paper,[1] we reported on an anomalous effect, evidenced in the near field of crossing microwaves beams, consisting of an unexpected transfer of modulation from one beam to the other, an effect which cannot be fully interpreted in terms of the usual electromagnetic or related framework. Thus, it was suggested that a mechanism of possible local breaking of the Lorentz invariance, elsewhere invoked for an alternative interpretation of superluminal behavior in these kind of systems,[2] could provide a partial explanation of the above results. Such a daring approach, however, deserves to be considered in much more detail before drawing any definitive conclusion.

The main purpose of this work is to report results obtained by an experiment of laser beams crossing, analogous to that of Ref. 1. However, before presenting these results, we briefly summarize the situation of the superluminality to which our results are strictly related.

As is well known, the principle that no signal can travel faster than the speed of light in vacuum is considered to be one of the basic laws of nature. Nevertheless, superluminal motions (that is, motions at velocities greater than light velocity) of wave packets and photons have been extensively demonstrated in a variety of situations. The question as to whether a wave packet can be considered a signal is much debated, however, and still remains an open question. According to Ref. 3, the superluminality evidenced in tunneling processes should be considered as being strictly confined within the domain of group velocity, which can never be extended to signal velocity. The point of view of Ref. 4 is different, with a crucial role being played by the spectral extension of any physical signal. A third, completely different approach has subsequently been proposed[2] and, if confirmed, would go well beyond the controversies of Refs. 3 and 4.

According to standard procedure,[5] the propagation of a pulse can be described by a contour integral in the complex plane of frequencies. By extending the integration domain to infinity, the forerunner of the signal cannot arrive before a time given by the distance traveled, L, divided by the light velocity c. However, by considering a finite spectral extension (in accordance with the physical evidence), the result obtained is that, for short distances (a localized effect), "something" can arrive earlier, at a time $t \leq L/c$.[6]

Recently, an answer to the above question was attempted[7] with a propagation experiment in a "fast-light" optical medium (similar to the one in Ref. 8), in which a point of non-analyticity was introduced on the top of Gaussian pulses for the purpose of realizing the conditions required for obtaining a signal. In this way, the authors of Ref. 7 claim to have demonstrated that no information can travel with velocity $v_i > c$, although the spectral extension of their signal is confined within a narrow fast-light frequency band of only 23 MHz (the carrier frequency is 389 THz). This interpretation has been criticized by Nimtz,[9] who estimated a greater spectral width, one which goes well beyond the narrow fast light window: this fact is at the origin of subluminal velocity of the aforesaid "signal". In the reply by Stenner *et al.*,[9] this criticism was rejected, holding the confinement of spectral extension within the fast-light range of frequency. However, in this case, we do not understand why the superluminal effect was not observed. We wish to note that, because of the limited spectral extension, the transition involved in Ref. 7 was quite smooth. Therefore, its actual beginning was rather uncertain, and this fact seems to make the proof not at all conclusive, also considering that the whole profile of the pulse showed an evident superluminal behavior.

Tunneling and, more in general, situations in which dispersion is present are characterized by different velocities, namely those related to phase, group and signal propagation. The cases in which dispersion is absent are different[10,11]: in these, all

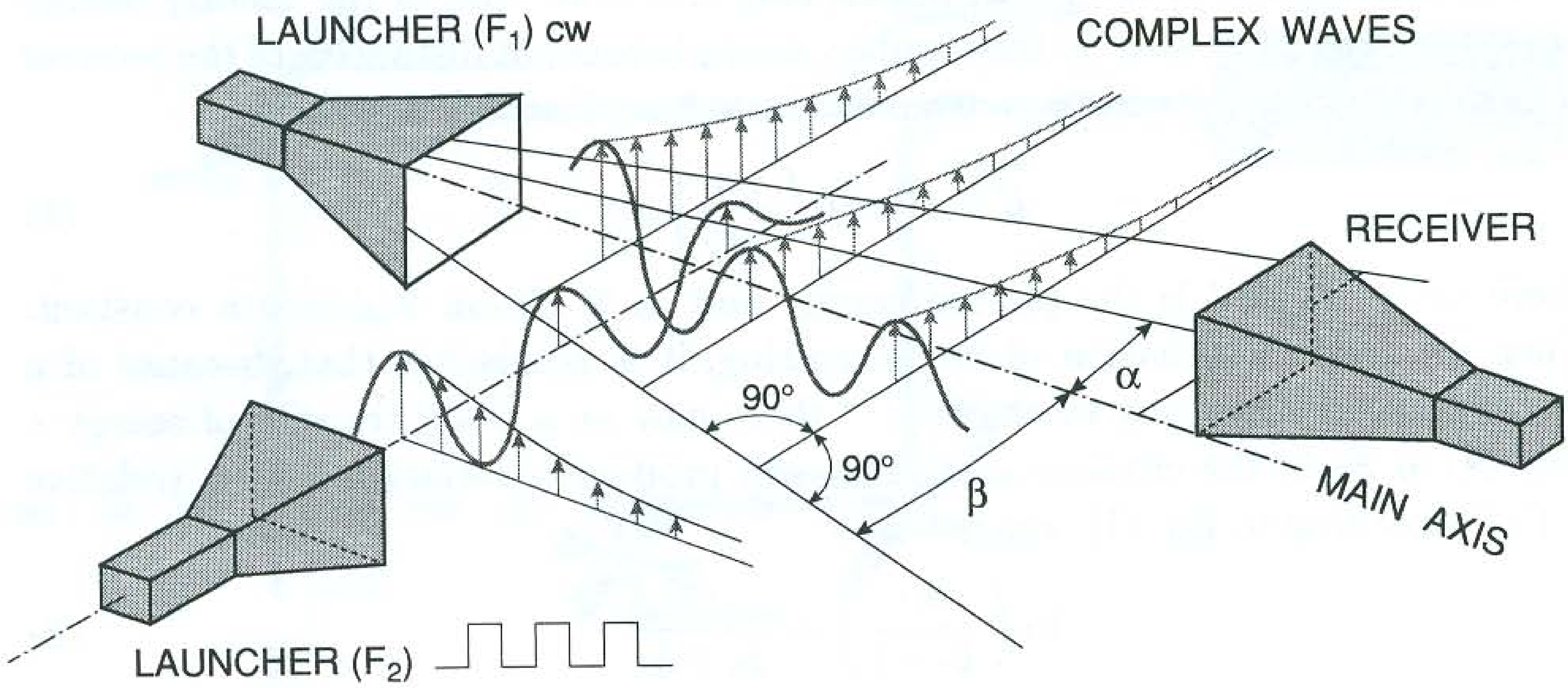

Fig. 1. Microwave propagation experiment (wavelength of about 3 cm) with three horn antennas, two as launcher and one as receiver. Field F_1 is a continuous wave (cw), while field F_2 is modulated. The receiver, placed sufficiently far from the interference area, detects only the modulated field. A special kind of decaying waves (complex waves) are operating at moderate distances from the launchers. The angle of observation is α, while β denotes the angle of propagation of F_1 with respect to the axis of the relative horn. Something similar holds for the waves (F_2) emitted by the second launcher.

the components in the spectral extension have the same propagation velocity. In these cases, the aforesaid velocities tend to be coincident. The results obtained for the group velocity could, presumably, thus be extended to the signal one, even if some caution is required since the definition of "signal velocity" is not universally shared.

In the microwave experiment of Ref. 1 (a modification of the one in Ref. 10), two horn antennas were used as launchers, while a third horn antenna, situated fairly far away from the intersection area, detected the effect of the crossing of the beams (see Fig. 1, taken from Ref. 12). In addition to the superluminal behavior already noted,[10] an anomalous effect, consisting of an unexpected transfer of modulation from one beam to the other (see Fig. 1 in Ref. 1), cannot be fully interpreted in terms of the usual electromagnetic or related framework. Rather, in order to explain this behavior, some kind of photon-photon scattering mechanism (similar to that produced by the presence of a nonlinear medium in the area of the beams intersection) was hypothesized, so as to justify the transfer of modulation also beyond the region of interference. As previously anticipated, a different interpretation of superluminality in this kind of system has been proposed within the framework of a Deformed Special Relativity (DSR), which hypothesizes situations of local broken Lorentz-invariance.[2] Avoiding the discussion of this delicate and controversial point, we prefer to follow a phenomenological approach already adopted in Ref. 1, in order to provide an explanation for the observed superluminal behavior (that is, when the ratio v/c is appreciably greater than the unity).

The attenuation of the beam power, and, therefore, also of the unitary energy (that is, energy E divided by the number, n, of photons) at distance z of the receiver from the launcher F_1, can be written as (hereafter, E stands for E/n):

$$E = h\nu \exp\left(-\frac{z}{z_0}\right), \tag{1}$$

where $h\nu = 37$ μeV is the photon energy and $z_0 \cong 30$ cm is a length constant. When we are in a situation of beam-crossing, it is admissible that, because of a photon-photon scattering mechanism,[13] there may be a small transfer of energy ε from F_2 to F_1 in the crossing area. This will produce a variation δ in z_0 (relative to F_1) according to Eq. (1), rewritten as

$$\ln\left(\frac{h\nu}{E+\varepsilon}\right) = \frac{z}{z_0+\delta}\,. \tag{2}$$

A variation in z_0, even if small ($\delta/z_0 = (z_0/z)\varepsilon/E$ was found to be of the order of some percent), can produce a relatively strong signal (the increment ε alone is modulated), similar to the ones reported in Ref. 1: there, near field cross talk and interference effects were also considered, but their contribution was found to be negligible. Therefore, the anomalous behavior observed can be justified and, in a sense, could be ascribed to the possibility of having a local broken Lorentz-invariance (according to Ref. 2, there should be a connection between a breakdown in the local Lorentz invariance and anomalous behavior in the photon-photon cross section). However, we have to recall that the near field supports the presence of complex or decaying waves[1,10,12] which play a role in interpreting these phenomena, and a theoretical model, one that revisits that of Ref. 2, can be worked out.

As a further test, we performed an optical experiment employing laser beams according to the geometry and technical details of Fig. 2. Laser beams have the advantage of very good alignment and beam confinement which defect in the case of microwave beams. The results obtained, however, did not give clear evidence of the effect (as in the case of microwave beams), because of a poor signal-to-noise ratio (see Fig. 3). Nevertheless, repetition of the measurements over observation times of a longer duration (15 minutes) provided the possibility of applying statistical tests to the averaged results, demonstrating that the statistics of the signal obtained in the presence or absence of beam crossing actually demonstrated a significant variation in the mean values. More precisely, let us consider the averaged value of the signal (which was measured in μV, with a lock-in sensitivity of 10 μV and integration time of 30 s). This averaged value, in the presence of beam crossing, and relative standard deviation, was found to be $\bar{X} \pm \sigma_X = -0.129 \pm 0.412$, while in the absence of crossing we had $\bar{Y} \pm \sigma_Y = 0.136 \pm 0.639$. Even if it seems that these results cannot be very well distinguished, their difference, which is given by $|\bar{X} - \bar{Y}| \pm \sigma_{X-Y} = 0.265 \pm 0.760$ (σ_{X-Y} is given by $(\sigma_X^2 + \sigma_Y^2)^{1/2}$) and the ratio $Z = |\bar{X} - \bar{Y}|/\sigma_{X-Y} \simeq 0.35$ are appreciable. In terms of probability, this means that we have a percentage of $\sim 14\%$ as being inside the above interval and of $\sim 36\%$ as being outside.[14]

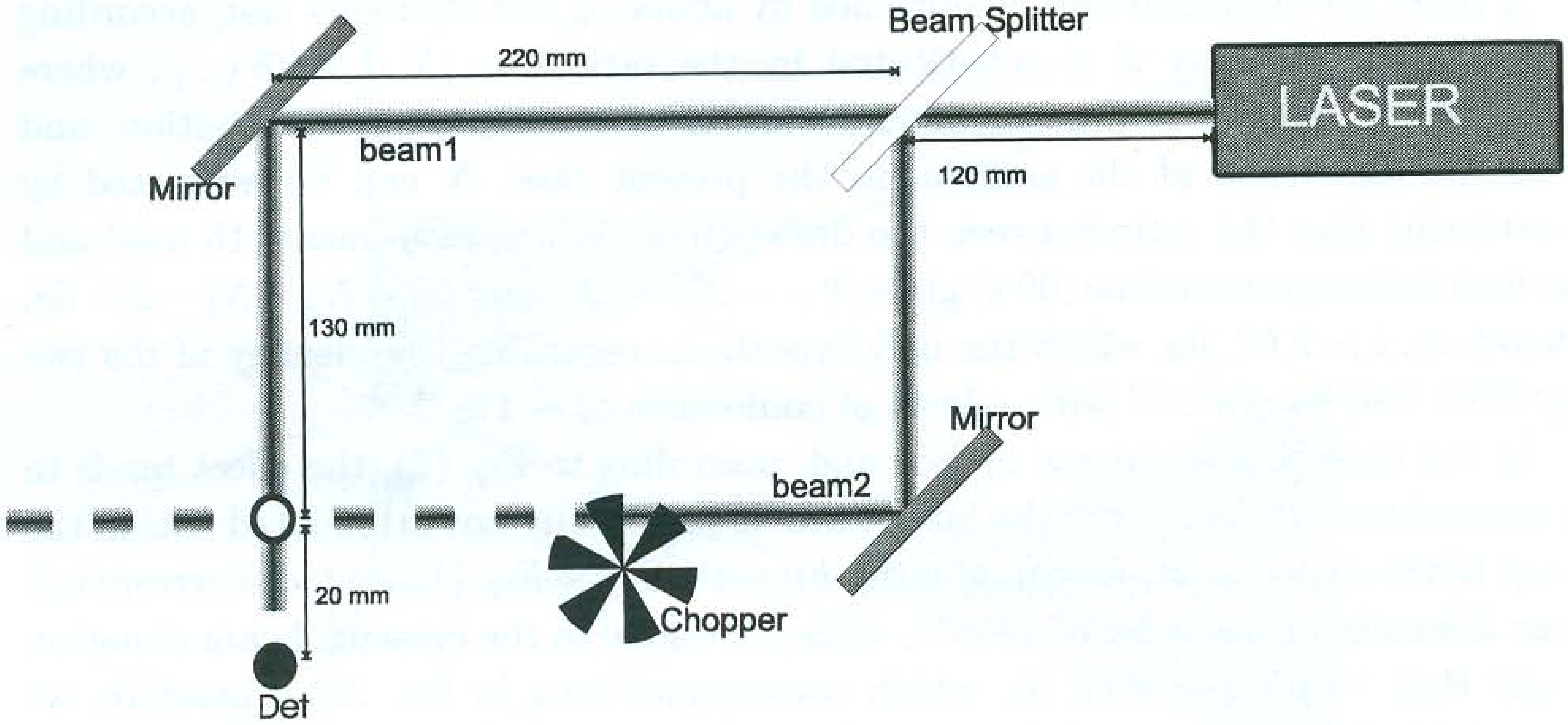

Fig. 2. Experimental setup using a CO_2 laser emitting at 10.6 μm on the fundamental TEM_{00} Gaussian mode. The laser beam is split in two orthogonal beams (beam 1 and beam 2) by means of a beam splitter. By using two flat mirrors the two beams are directed to the crossing point (denoted by a circle) within the near field of the Gaussian mode estimated at 1.5 m from the outcoupler mirror of the laser cavity. Beam 2 is periodically interrupted by means of a chopper whose frequency is the reference frequency in a lock-in amplifier connected to the detector (Det). Particular attention was paid to avoid spurious effects such as diffusions and reflections due to the chopper or others surfaces situated near the optical path, and even beyond the crossing point.

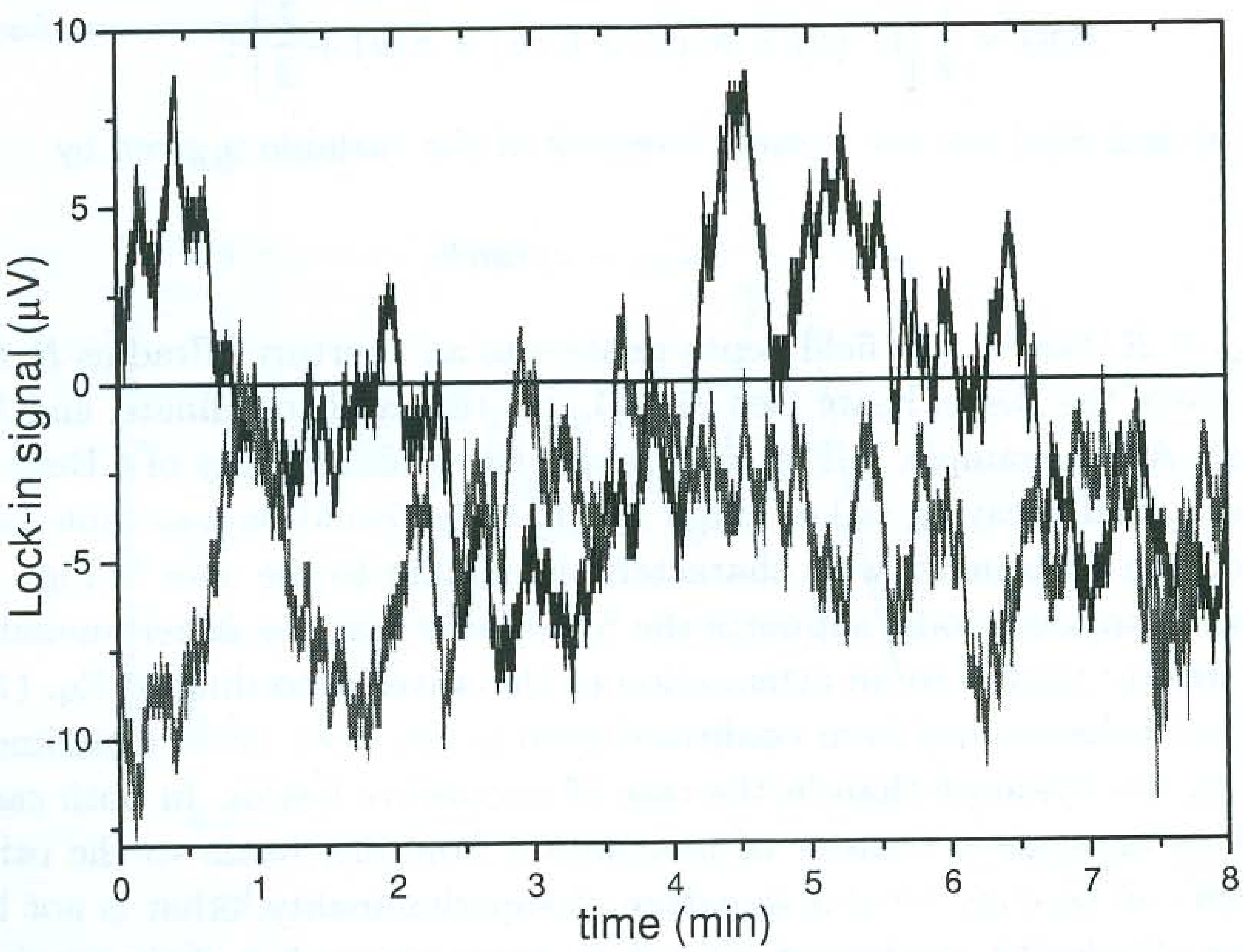

Fig. 3. An example of output signal of the lock-in amplifier (sensitivity of 50 μV and integration time of 10 s), in the presence of the chopped beam 2 (red line) and in its absence (black line), over a relatively long observation time. In spite of the poor signal-to-noise ratio, we observe an appreciable variation in the mean value of the two cases.

A more precise result can be obtained by adopting the student's test, according to which the quantity Z is substituted by the ratio $t = |\bar{X} - \bar{Y}|/\widehat{\sigma}_{X-Y}$, where $\widehat{\sigma}_{X-Y} = \sigma_{X-Y}/\sqrt{N}$ is the standard deviation of the sampling distribution, and N is the dimension of the sample. In the present case, N can be estimated by considering that the ratio between the duration of each measurement (15 min) and the lock-in integration time (30 s) gives $N_X = N_Y = 30$, and $N = N_X + N_Y - 2 = 58$. Therefore, $t \simeq 2.67$, for which the null hypothesis regarding the identity of the two statistics can be rejected with a level of confidence of $\sim 1\%$.[15]

In the case of laser beams $z_0 \gg z$ and, according to Eq. (2), the effect tends to be less evident. In fact, since the laser beam is practically not attenuated within the range of the experiment, we can identify $h\nu$ with E (see Eq. (1)), which corresponds to an intensity of the order of 10 mV, while the signal in the crossing beam situation is less that 10 μV (see Fig. 3), which corresponds to ε in Eq. (2). Therefore, we have $\ln(h\nu/E + \varepsilon) \simeq -\varepsilon/E \simeq z/z_0 \lesssim 10^{-3}$, a value that for $z \simeq 1$ m gives $z_0 \gtrsim 1$ km, in agreement with the laser beam characteristics.

According to these considerations, a more promising optical source, one which better reproduces the characteristics of the microwave experiment (decaying waves with z_0 of smaller value), can be obtained by using suitably shaped Bessel beams.[11,16] In fact, by denoting the radial coordinate with ρ, the propagation of the central peak intensity, $I(\rho = 0, z)$ of a Bessel beam can be simply described, according to the *shadow's theorem*,[17] as

$$I(u) = \frac{1}{2}\left[C^2(u) + S^2(u) + C(u) + S(u) + \frac{1}{2}\right], \qquad (3)$$

where $C(u)$ and $S(u)$ are the Fresnel integrals of the variable u given by

$$u = \sqrt{\frac{2}{\lambda z}}(z_{\max} - z)\tan\theta\,. \qquad (4)$$

Here, $z_{\max} = R/\tan\theta$ is the field depth relative to an aperture of radius R, θ is the axicon angle of the Bessel beam (see Fig. 4), z is the axial coordinate, and λ is the wavelength. As an example, in Fig. 5 we report the peak intensity of a Bessel beam that shows a final decaying tail of about 1.5 m, which could be a suitable value for carrying out an experiment with characteristics similar to the ones in Fig. 1.

In conclusion, our model supports the hypothesis that the superluminality observed is strictly related to an attenuation of the waves according to Eq. (1). The superluminal behavior has been confirmed even in the laser beam experiment, although with less evidence than in the case of microwave beams. In both cases, we evidenced an anomalous transfer of modulation from one beam to the other, an effect which can be considered a signature of superluminality,[1] that is not limited to the type of velocity considered. Therefore, in consideration of the results (and the proposal) presented here for their implications to propagation velocities, the question as to whether superluminal behavior can be extended or not to information velocity is still lacking in conclusive proof, and further investigations will have to be made before any definite conclusion can be safely drawn.[18]

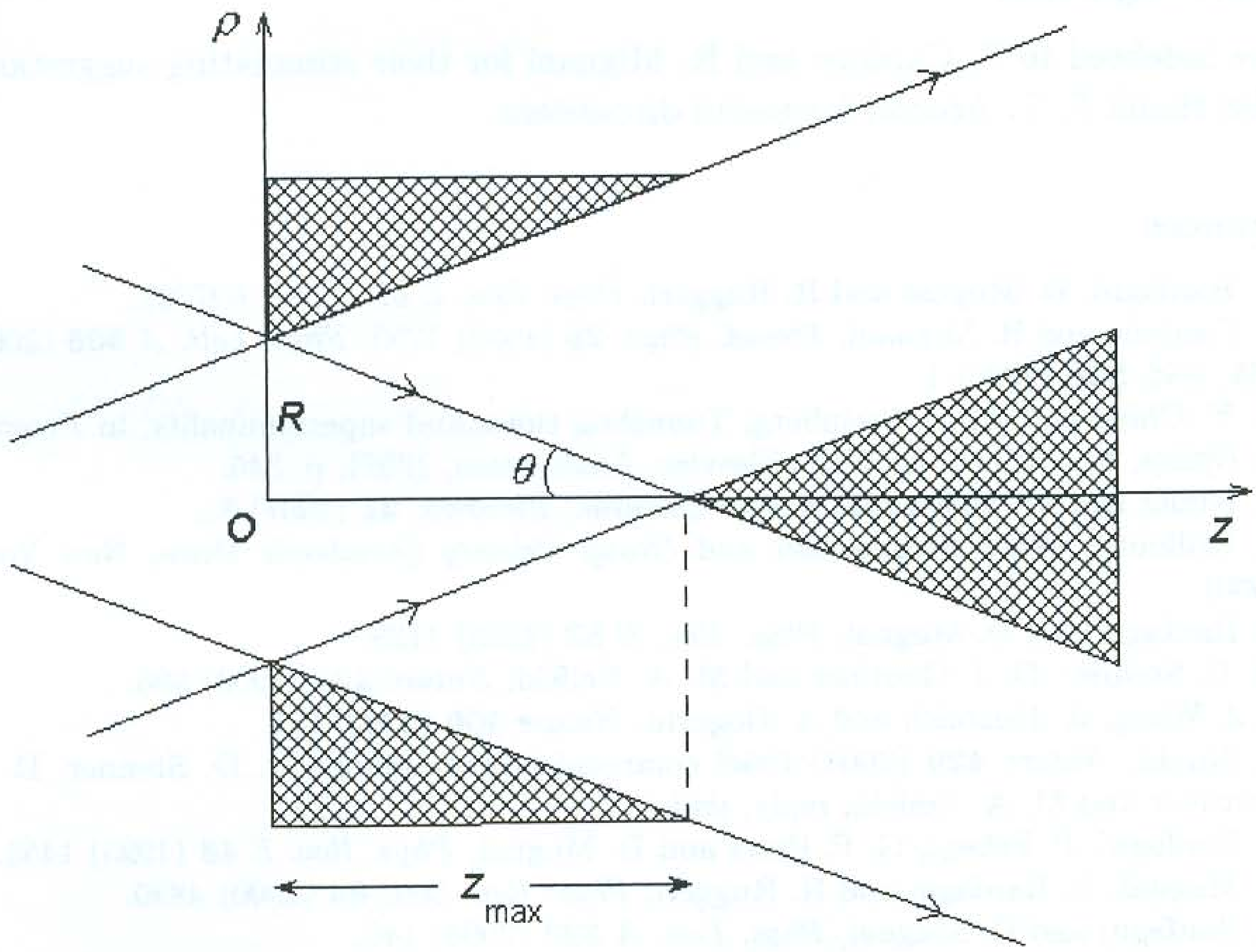

Fig. 4. Geometrical construction of the shadow zones for a Bessel beam of finite aperture of radius R and axicone angle θ.

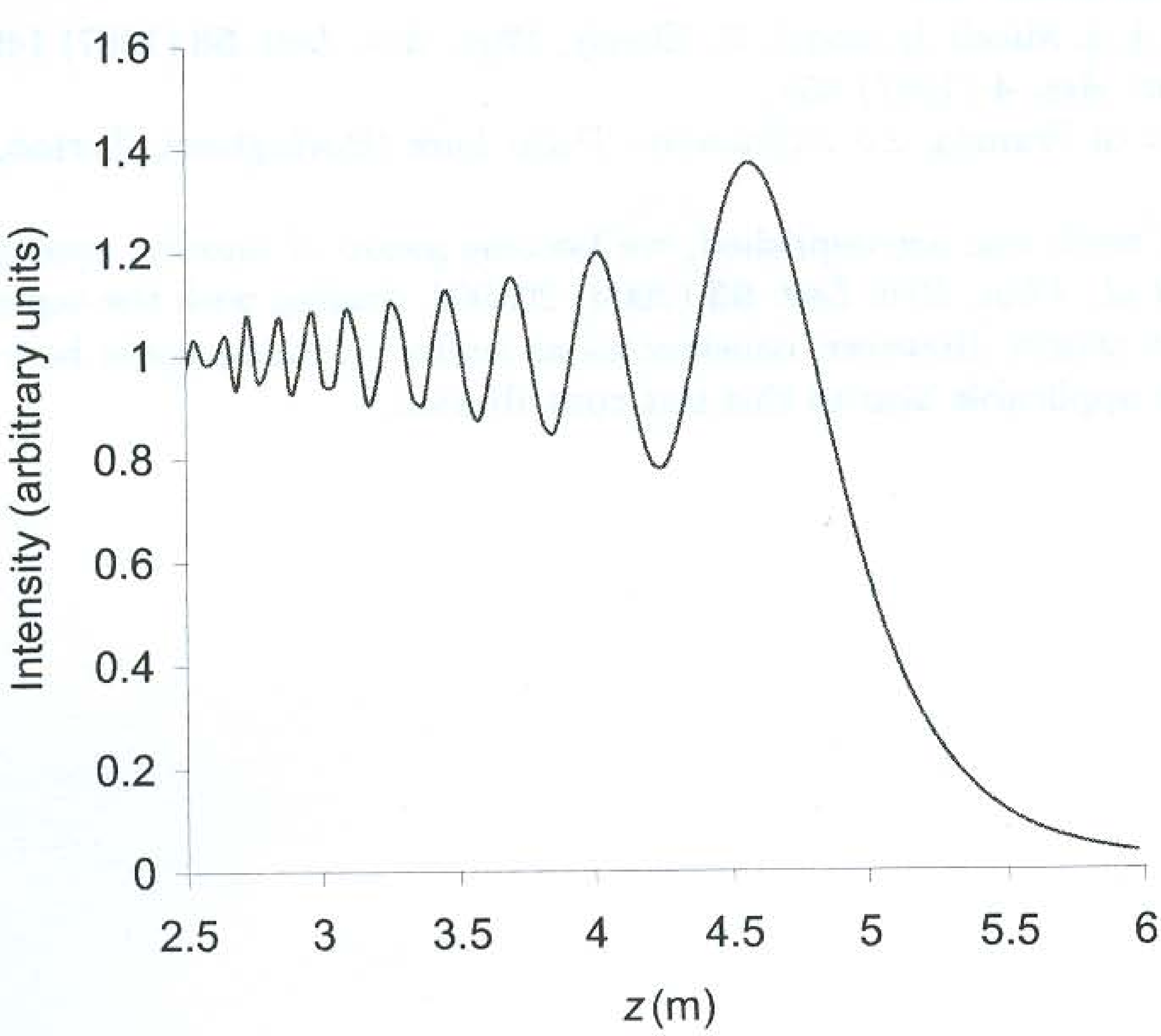

Fig. 5. Intensity of the central peak of a Bessel beam as a function of the distance z, for $R = 10$ mm, $\tan\theta = 1.9 \times 10^{-3}$, $\lambda = 0.5$ μm.

Acknowledgments

We are indebted to F. Cardone and R. Mignani for their stimulating suggestions. We also thank F. T. Arecchi for useful discussions.

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