# Unexpected behavior of crossing microwave beams

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An anomalous effect in the near field of crossed microwave beams, consisting in an unexpected transfer of modulation from one beam to the other, cannot be fully interpreted, at least not in a simple way, in terms of the usual electromagnetic or related framework. It is hypothesized that a local breaking of the Lorentz invariance, already invoked for an alternative interpretation of superluminal behaviors in these kinds of systems, could provide a partial explanation of the present results, although other interpretations cannot be completely ruled out.

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Superluminal motions (that is, motions at velocities greater than the light velocity in vacuum) of wave packets and photons have been extensively studied and demonstrated in a variety of situations such as subcutoff waveguide propagation [1], wave-packet propagation in the near-field [2,3], and stop-band optical filters [4,5]. These types of behavior were interpreted within the framework of the usual electromagnetic theory or, equivalently, within that of quantum tunneling, properly translated into the electromagnetic framework, including the possibilities offered by a stochastic modelization of tunneling processes [6].

The importance of the results reported in the present work lies in the fact that they cannot be fully interpreted, at least not in a simple way, in terms of the usual electromagnetic or related framework. A completely different interpretation of these results can be envisaged within a framework of deformed special relativity (DSR) which hypothesizes situations of broken Lorentz invariance [7,8]. Rather surprisingly, it is just the hypothesis of the broken Lorentz invariance which could be capable of supplying a relatively simple interpretation, in spite of understandable skepticism that such an assumption can arouse [9]. The main purpose of the present work, however, is to report on the results of a microwave experiment, leaving the problem of their interpretation without a definitive answer.

The experiment consisted in measuring, as a function of the attenuation, the signal received at a given distance from the area of interference (or better, of interaction) of two crossing microwave beams at ~9.5 GHz. The geometry of the experimental setup, employing three horn antennas, two as launchers and one as receiver, is shown by the inset in Fig. 1. The main beam, or field ($F_1$), was without modulation, while the secondary beam, or field ($F_2$), was modulated by a square wave with a repetition frequency of ~1500 Hz. Both beams were derived by the same generator, in order to ensure the coherence of the two fields produced.

The first measurement was performed with both beams with vertical polarization (vp), that is, with the electric field perpendicular to the plain of the inset in Fig. 1. The initial signal (0 dB of attenuation) was about 440 $\mu$V, as measured, after crystal detection, by a lock-in amplifier. By increasing the attenuation of $F_1$ (while $F_2$ was maintained at its maximum value) up to 40 dB, we observed the decrease reported in Fig. 1, with an oscillating and damped shape up to a residual value of about 10 $\mu$V. By increasing the attenuation of $F_2$ (while, this time, $F_1$ was maintained at the maximum value), we observed a constant decrease from the same initial value (~440 $\mu$V) to the same residual (~10 $\mu$V).

The ratio of the two levels, referred to each beam separately, with 0 dB of attenuation, at the receiver was found to be ~30 dB, which corresponds to a value of 1/1000, to the point of representing a modest interference effect between the two beams directly on the detector system [10]. This supports the hypothesis that we are presumably in presence of an anomalous type of behavior and that the simple interference is not sufficient to interpret the results.

As a confirmation of this fact, the experiment repeated with the beam $F_2$ in horizontal polarization (hp), that is, with the electric field parallel to the plane of the inset in Fig. 1, maintaining $F_1$ in vp, showed a completely analogous behavior, even if with minor intensity (see Fig. 1). The initial value of the signal (~180 $\mu$V) was a little less than one-half of the previous one. For a normal interference, with orthogonal polarizations, the effect should nearly disappear. In fact, the interference term of the type $(\mathbf{E}_1 \cdot \mathbf{E}_2)\cos\theta$, where $\mathbf{E}_1$ and $\mathbf{E}_2$ are the electric fields of the two beams and $\theta$ is the spatial

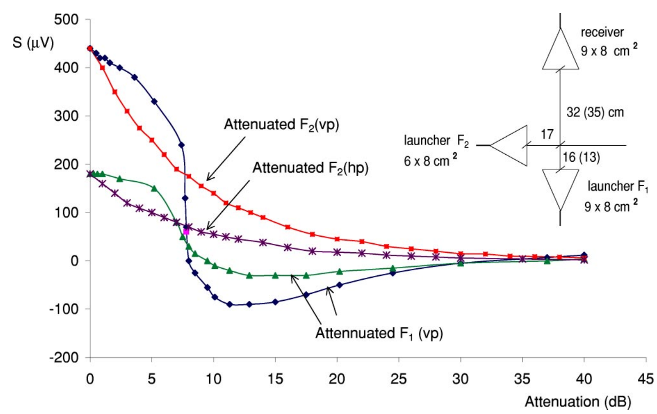


FIG. 1. Signal amplitude $S$ as measured by the lock-in amplifier connected to the receiver, with $F_1$ and $F_2$ in vertical polarization (vp), as function of the attenuation of $F_1$ (diamonds) or of the attenuation of $F_2$ (squares). When $F_2$ was in horizontal polarization (hp) the initial signal was lowered but the shapes as function of the attenuation of $F_2$ (crosses) or of $F_1$ (triangles) are similar to the previous ones. The geometry of the experiment is given in the inset; the quotes in parenthesis refer to the case of $F_2$ in hp, the mouth sizes of the horn antennas are also indicated.

 

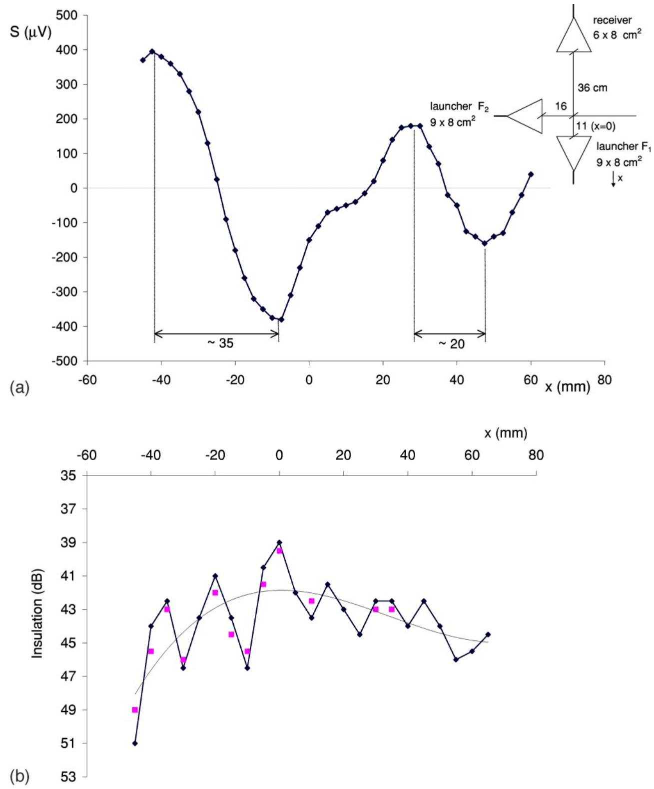


FIG. 2. (a) Same as Fig. 1, with $F_1$ and $F_2$ in vp and no attenuation, as function of the position ($x$ coordinate in the inset) of the launcher $F_1$; (b) measured insulation between the horns having $F_2$ as launcher and $F_1$ as receiver. The continuous line represents an ''average'' of the data.

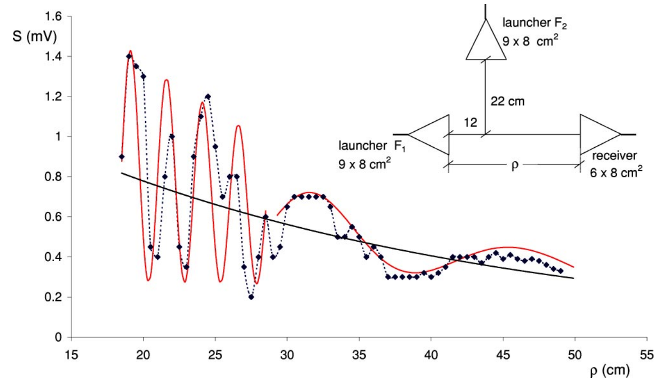


FIG. 3. Signal amplitude measured by the lock-in amplifier connected to the receiver, with $F_1$ and $F_2$ in vertical polarization, as a function of the distance $\rho$ from the launcher $F_1$. In the initial region, $\rho \leqslant 28.5$ cm, we observe a rapid damped oscillation with a period of $\sim 2.5$ cm. In the subsequent region, $\rho \geqslant 28.5$ cm, we have a slow damped oscillation with a period increasing from 10 to 14 cm. The average of the signal is described by an exponential decay with constant $\rho_0 = 30.5$ cm.

dephasing, should become zero and only a small residual amplitude is admissible.

The detected signal, however, turned out to be strongly dependent on the reciprocal position of the two launchers, so that we can suppose that the interference—which certainly subsists in the area of beams crossing—could be responsible (in some way) for the phenomenon observed. Figure 2(a) shows the shape of the detected signal as a function of the position of the $F_1$ launcher, denoted by the coordinate $x$ [see the inset in Fig. 2(a)]. With an increase in $x$, we observed an oscillating and decreasing shape, with a half period that decreases from a value of $\sim 35$ mm to one of $\sim 20$ mm. This last aspect can be interpreted on the basis of the existence of the complex waves (see Fig. 1 in Ref. [11]) that characterize the near field produced by the launcher antennas. By assuming that the half period in Fig. 2a corresponds to a half-effective wavelength, the ratio $\lambda_{\mathrm{eff}}/\lambda_0$ (with $\lambda_0 \simeq 32$ mm) varies from $\sim 2.2$, in the nearest region of $F_1$ launcher (negative values of $x$), to $\sim 1.25$ in the farthest region (positive values of $x$). These values are directly related to the superluminal effect, since they correspond to the ratio $u/c$ $(=\lambda_{\mathrm{eff}}/\lambda_0)$ of the observed velocity ($u$) to the light velocity in vacuum ($c$), as predicted by the complex-wave model. The latter, however, seems to be inadequate in explaining the strong signal observed, especially when the distance of the receiver is increased (see below, in relation to Fig. 3).

TABLE I. Summary of data and results of a two-horn antenna experiment, after Ref. [2]. $L$ and $l$ represent the longitudinal and transverse displacements, respectively, of the two horns, while $\rho$ is their distance. The angles $\alpha$ and $\beta$ denote the direction of observation and the direction of the complex waves, respectively. The ratio $b_{\mathrm{em}} = c/u = \cos(\alpha+\beta)\cosh(\beta_i)$ was evaluated by assuming that $\beta_i$ (the imaginary part of $\beta$) is practically zero, so that $\cosh \beta_i \simeq 1$. The attenuation constant $A_{\mathrm{att}} = (2\pi\rho/\lambda_0)\sin(\alpha+\beta)\sinh \beta_i$ was estimated by assuming the value of 0.02 for the product $\sin(\alpha+\beta)\sinh \beta_i$, in order to have results compatible with the measured levels.

| $L$ | $l$ | $\rho$ $(=\sqrt{L^2+l^2})$ | $\alpha$ $[=\tan^{-1}(l/L)]$ | $\beta$ | $b_{\mathrm{em}}$ $(=c/u)$ | $b_s$ $(=\tau_a/\tau_0)$ | $A_{\mathrm{att}}$ | $f$ $(=e^{-2A_{\mathrm{att}}})$ | $E/N = fh\nu$ $(h\nu = 37\ \mu$ eV) |
|---|---|---|---|---|---|---|---|---|---|
| (cm) | (cm) | (cm) | (deg) | (deg) | | | | | ($\mu$ eV) |
| 21 | 15 | 25.8 | 35.5 | 25 | 0.49 | $\sim 0.1$ | 1.02 | 0.13 | 4.81 |
| 49 | 22 | 52.9 | 24.2 | 25 | 0.65 | 0.66 | 2.10 | $15\times10^{-3}$ | 0.55 |
| 61 | 25 | 65.9 | 22.3 | 25 | 0.68 | 0.73 | 2.62 | $5.3\times10^{-3}$ | 0.20 |
| ... | ... | 72 | 25 | 20 | 0.71 | 0.75 | 2.86 | $3.3\times10^{-3}$ | 0.12 |
| ... | ... | 83 | 25 | 20 | 0.71 | 0.83 | 3.30 | $1.4\times10^{-3}$ | 0.05 |
| 99 | 30 | 102 | 16.8 | 25 | 0.74 | 0.94 | 4.06 | $0.3\times10^{-3}$ | 0.01 |
| 111 | 30 | 115 | 15.1 | 25 | 0.76 | $\sim 1$ | 4.56 | $0.1\times10^{-3}$ | 0.004 |

Another possible mechanism which can produce a transfer of modulation from one beam ($F_2$) to the other beam ($F_1$) has to be envisaged in the mutual influence between the two launchers. Since the two horns are within their near fields, they are coupled together and the field from one can modulate the radiated field on the other (near-field cross talk). The cross talk phenomenon is often a problem, but it can be also useful since it is employed in several kinds of devices [12]. In order to do an estimate of its effect, we have measured the insulation between the two horns, taking one ($F_2$) as launcher and the other ($F_1$) as receiver. The results, as function of the reciprocal position of the two horns, are shown in Fig. 2(b). First of all, we note that by comparing the shape of the data in Fig. 2a with those in Fig. 2(b), it is difficult to recognize any kind of correlation between them: a correlation which should be reasonably envisaged if the observed effect [Fig. 2(a)] would be due only to the coupling between the two horns. Moreover, the measured insulation (of at least ~40 dB) corresponds to an induced level on the launcher $F_1$ of the order of 100 $\mu$V, which become of the order of a few microvolts at the receiver of the main experiment. Over an equivalent level of ~1 V at the mouth of the launcher $F_1$, 100 $\mu$V represent only the 0.01%, a value completely inadequate for explaining the observed effect (~400 $\mu$V over ~10 mV at the receiver in the main experiment, see Ref. [10]) equal to ~4%.

As a further test we measured the signal detected by the receiver horn as a function of the distance $\rho$ from the launcher $F_1$ (see the inset in Fig. 3). The results obtained, with both beams with vertical polarization, are shown in Fig. 3: we see a damped oscillating behavior around an exponential decay $S(\rho) \propto \exp(-\rho/\rho_0)$, with $\rho_0 = 30.5$ cm. In the initial portion ($\rho \leqslant 28.5$ cm), the oscillation has a nearly constant period (equal to λ/2 in the present case) of about 2.5 cm, while in the subsequent portion ($\rho \geqslant 28.5$ cm) the period suddenly increases to 10–14 cm. The behavior in the initial portion can be ascribed to an interference effect between the two beams which produces an evident transfer of modulation from $F_2$ to $F_1$. According to the model of Ref. [2], the interference in the initial portion can be interpreted by the existence of complex waves that characterize the near field produced by the two launchers. By means of the expressions reported in Table I, the data for $\rho \leqslant 28.5$ cm can be approximately fitted (for $\alpha = 0$) by assuming for $\beta$ the value of the complete flare angle of the horns ($\beta = 50°$), and for $\beta_i$ (the imaginary part of $\beta$) a value of the order of a few degree (so that $\cosh \beta_i \approx 1$), which is a reasonable one [2]. By these parameter values, the ratio between the propagation velocity $u$ and the light velocity $c$ is $u/c = 1.56$ [a value comprised in the interval ~1.25 and ~2.2, as deduced before from Fig. 2(a)] which confirms a superluminal behavior.

More problematic is the interpretation in the subsequent region where a period of 10–14 cm appears a disproportionate one for an explanation in terms of an interference, even considering the residual tails of the complex waves.

So, we are tempted to search for a different way to interpret the behavior observed, not simply on the basis of an interference at the position of the receiving antenna, or on the basis of a mutual influence between the two launchers, but rather as if a *nonlinear medium* would be situated in the area of beams' intersection, so to allow a sufficient transfer of modulation from one beam ($F_2$) to the other ($F_1$).

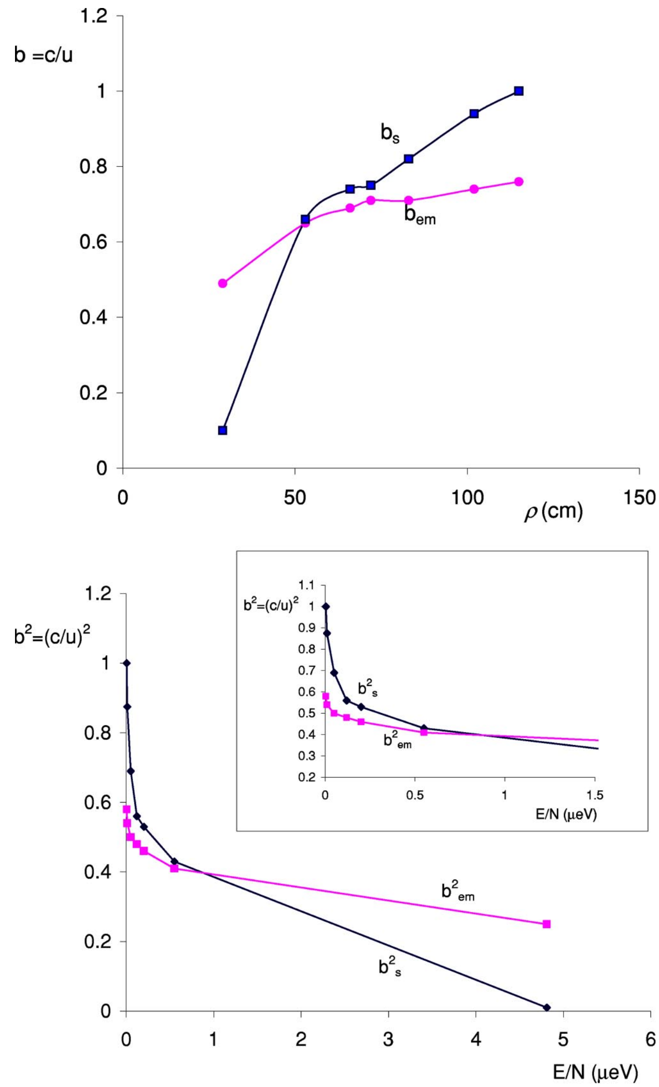


FIG. 4. In (a) we report values of the ratio $c/u$ as reduced from delay measurements ($b_s$) and from the complex-wave model ($b_{\rm em}$) as function of the distance $\rho$ between the launcher and the receiver antennas (after Ref. [2]). In (b) the square $(c/u)^2$ of the same values is reported as function of the residual unitary energy $E/N$. The $b_s^2$ values can be roughly fitted by Eq. (1) with $E_0 = 5$ $\mu$eV and $n = 7$; the $b_{\rm em}^2$ values can be described by a different choice of parameter values.

To this end, let us reconsider the results of Ref. [2], relative to two horn antennas (one as launcher and the other as receiver), always on the basis of the complex-wave model described therein. The salient results are summarized in Table I. In Fig. 4a we report the values of the ratio $b_s = \tau_\alpha/\tau_0$ between the measured delay $\tau_\alpha$, and the delay $\tau_0$ corresponding to the light velocity, as a function of the distance $\rho$ between the launcher and the receiver antennas. In the same figure, we report also the ratio $b_{\rm em} = c/u$, as resulting from the electromagnetic model. From an examination of Fig. 4(a), we note that, except for the value of $b_s \simeq 0.1$, which is decidedly in disagreement with the corresponding $b_{em} \simeq 0.5$, the other values are in reasonable agreement. The discrepancy increases with increasing $\rho$. This can be explained by considering that, when $\rho$ becomes of the order of 1 m, the contribution of the normal wave becomes predominant with respect to that of the complex waves, and the anomalous effect (the superluminal motion) is masked (see Fig. 5 in Ref. [11]). In the penultimate column of Table I, we report the square of the attenuation of the field, which represents the attenuation of the power and, therefore, also of the energy. In the last column, we report the residual unitary energy (that is divided by the number $N$ of the photons) at the distance $\rho$ of the receiver. In Fig. 4(b) we report data of $b^2 = (c/u)^2$, according to the values of Fig. 4(a), but situated at the corresponding values of $E/N$.

Let us assume that the interpretation of the superluminal behavior as given in Refs. [7,8], which is in the framework of the DSR theory, is correct. Here, we do not discuss the rightness or less of such an interpretation; rather, we simply adopt it as a framework. Accordingly, when $b^2$ is appreciably less than unity, we should be in local situations of broken Lorentz invariance. At a distance $\rho \lesssim 20$ cm (the mean distance of the intersection area from the launchers in the present experiment), such an effect should be much evident ($b^2 \lesssim 0.5$) in order to justify the anomalous effect observed, according to the following reasoning.

Figure 4(b) shows an indubitable dependence of $b^2$ on the energy $E$ (hereafter, $E$ stands for $E/N$). According to the above assertion, $b^2 < 1$ is representative of clear anomalous behavior (superluminal motion), but also has the role of a nonlinear medium, as hypothesized previously. The dependence of $b^2$ on $E$ can be described by a form such as [see Fig. 4(b)]

$$b^2(E) \equiv (c/u)^2 = \left(1 - \frac{E}{E_0}\right)^n \qquad (1)$$

with $E \leqslant E_0$. Thus, when $E = 0$, $b^2 = 1$ and we resume the normal type of behavior. On the other hand, the attenuation of the energy can be written as $E = h\nu \exp(-\rho/\rho_0)$, where $h\nu$ is the photon energy and $\rho_0$ is a length constant (see Fig. 3). By inverting, we have

$$\frac{\rho}{\rho_0} = \ln\left(\frac{h\nu}{E}\right). \qquad (2)$$

Let us admit that in a beam-crossing situation, in the crossing area, there is a transfer of energy $\varepsilon$ from $F_2$ to $F_1$, as the consequence of a further "space deformation" due to $F_2$, in addition to the one due to $F_1$. This will produce a variation $\delta$ of $\rho_0$ (relative to $F_1$) according to Eq. (2) rewritten as

$$\ln\left(\frac{h\nu}{E+\varepsilon}\right) = \frac{\rho}{\rho_0 + \delta}. \qquad (3)$$

But it is simply an increment of $\rho_0$ [even if it is very small: $\delta/\rho_0 = (\rho_0/\rho)\varepsilon/E$ will be of the order of a few percent] which can produce a relatively strong signal (if the increment $\varepsilon$ alone is modulated) similar to the ones reported in Fig. 1.

Therefore, it seems that the behavior observed could be ascribed, at least partially, to a local broken Lorentz invariance. This assumption seems to provide a simple interpretation of the experimental observation. Such daring approach to the problem, however, deserves to be considered in more detail before any serious conclusion can be safely drawn. Other interpretations cannot be ruled out [13]. The interference effect (which is certainly present in the area of beam crossing and survives, although attenuated, even at the receiver position) and the cross talk between the two launchers seem to be inadequate to account for the strong observed effect, even if some role could be played as concomitant effects.

We are indebted to F. Cardone and R. Mignani for helpful discussions and suggestions.


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[10] The level measurements were performed by using a "standing-wave indicator" with a square law detector. With a level of $F_1$ measured by this detector of ~10 mV, the level of $F_2$ resulted to be of a few microvolts, nearly two orders of magnitude less than the signal obtained when both beams (but only $F_2$ modulated) were present (~440 $\mu$V). When both beams were modulated, we observed an increase of the signal of ~0.15 dB, which corresponds to an increase of ~3%, that is ~600 $\mu$V, value which is comparable with the one measured by the lock-in amplifier.

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[13] More refined analyses of the data are still in progress, but this overcomes the aim of the present work, which is mainly devoted to reporting the results of an experiment.