Superluminal signal velocity

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Abstract. It recently has been demonstrated that signals conveyed by evanescent modes can travel faster than light. In this report some special features of signals are introduced and investigated, for instance the fundamental property that signals are frequency band limited. Evanescent modes are characterized by extraordinary properties: Their energy is negative, they are not directly measurable, and the evanescent region is not causal since the modes traverse this region instantaneously. The study demonstrates the necessity of quantum mechanics in order to understand the superluminal signal velocity of classical evanescent modes.

1 Introduction

Tunneling represents the wave mechanical analogy to the propagation of evanescent modes [1]. Evanescent modes are observed, e.g. in the case of total reflection, in undersized waveguides, and in periodic dielectric heterostructures [2]. Compared with the wave solutions an evanescent mode is characterized by a purely imaginary wave number, so that the wave equation yields for the electric field E(x)

$$E(x) = E_0\, e^{i(\omega t - kx)} \quad \Rightarrow \quad E(x) = E_0\, e^{i\omega t - \kappa x},$$

- Equation 1 -

where w is the angular frequency, t the time, x the distance, k the wave number, and Kappa = ik the imaginary wave number of the evanescent mode. are shown in Fig. 1 [2]. Thus evanescent modes are characterized by an exponential attenuation and a lack of phase shift. The latter means that the mode has not spent time in the evanescent region, which in turn results in an infinite velocity in the phase time approximation neglecting the phase shift at the boundary [3]. Two examples of electromagnetic structures are shown in Fig. 1 [2] in which evanescent modes exist. The dispersion relations of the respective transmission coefficients are displayed in the same figure.

2 Signals

Quite often a signal is said to be defined by switching on or off light. It is assumed that the front of the light beam informs my neighbor of my arrival home with the speed of light. Such a signal is sketched in Fig. 2. The inevitable inertia of the light source causes an inclination of the signal's front and tail. Due to the detector's

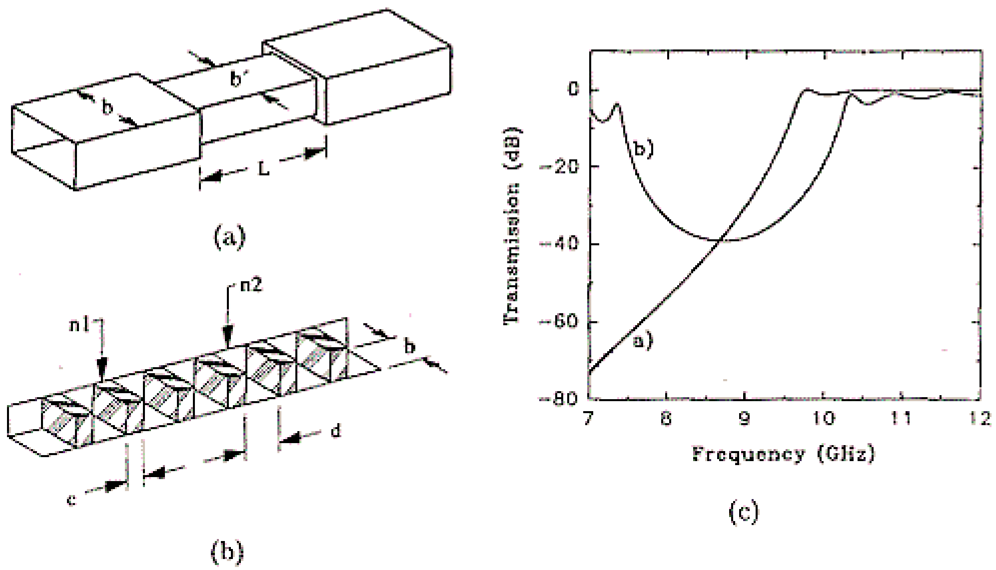


Fig. 1 Two examples of electromagnetic structures with evanescent mode solutions: (a) of a waveguide with an undersized central part and (b) a one-dimensional periodic hetero-structure. n1 and n2 are the refractive indices and c and d the thickness of the dielectric materials. In (c) the graphs show the dispersion relations for both structures. The transmission dispersion of the periodic heterostructure displays a forbidden gap which corresponds to a tunneling regime, for details see Ref. [2]. The evanescent regime is characterized by a strong attenuation due to the exponential decay.

sensitivity level Ds, the information about my arrival (switching on) and departure (switching off) becomes dependent on intensity. In this example the departure time is detected earlier with the attenuated weak signal.

This special signal does not transmit reliable information on arrival and departure time. In addition to the dependence on intensity, a light front may be generated by any spontaneous emission process or accidentally by another neighbor. Obviously, a detector needs more than a signal's front to response properly. The detector needs information about carrier frequency and modulation of the signal in order to obtain reliable information about the cause.

In general, a signal is detected some time after the arrival of the light's front. Due to the dynamics of detecting systems there are several signal oscillations needed in order to produce an effect [1]. An effect is detected with the energy velocity. In vacuum or in a medium with normal dispersion the signal velocity is equal to both, the energy and the group velocities.

For example, a classical signal can be transmitted by the Morse alphabet in which each letter corresponds to a certain number of dots and dashes. In general signals are either frequency (FM) or amplitude modulated (AM) and they have in common that the signal does not depend on its magnitude. A modern signal transmission, where the halfwidth corresponds to the number of digits, is displayed in Fig. 3. This AM signal has an infra-red carrier with 1.5 mu wave length and is glass fiber guided from transmitter to receiver. As mentioned above, the signals are independent of

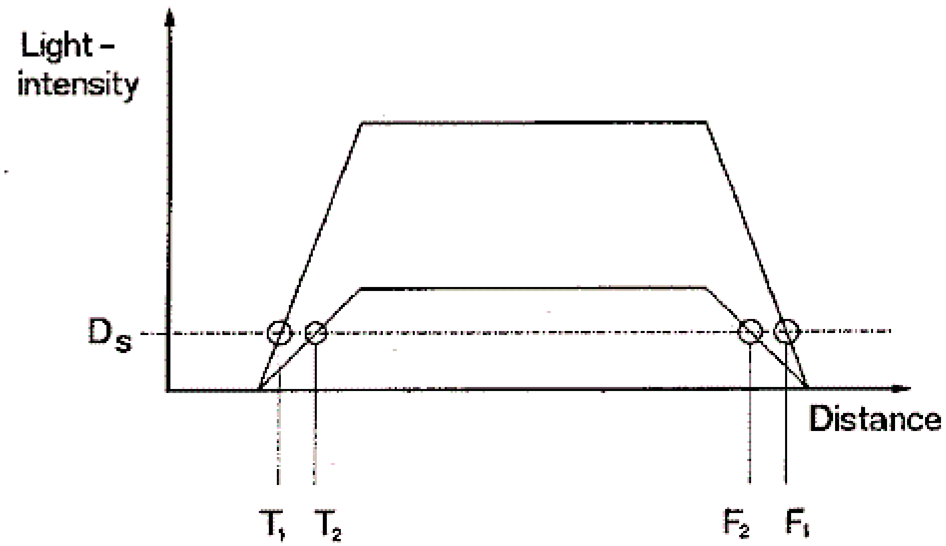


Fig. 2 Sketch of a light train. The two detected fronts of the same attenuated and not attenuated light beam are F1, F2 and the tails are T1, T2. They are measured at different places and times in consequence of the detector's response level Ds.

magnitude as the halfwidth does not depend on the signal's magnitude.
The front or very beginning of a signal is only well defined in the theoretical case of an infinite frequency spectrum. However, physical generators only produce signals of finite spectra. This is due to their inherent inertia and due to a signal's finite energy content. In the case of an infinite signal spectrum, the Planck relation would necessarily result in an infinite signal energy.
These properties result in a real front which is defined by the measurable beginning of the signal. For example, the signals of Fig. 3 have a detectable frequency band width of $\Delta\nu = \pm 10^{-4} \times \nu_C$, where vc is the carrier frequency.
Frequency band limitation in consequence of a finite signal energy reveals one of the fundamental deficiencies of classical physics. A classical detector can detect a deliberately small amount of energy, whereas every physical detector needs at least one quantum of the energy in order to respond.

3 An experimental result

Superluminal signal velocities have been measured by Enders and Nimtz [4, 5, 6]. The experiments were carried out with AM microwaves in undersized waveguides and in periodic dielectric heterostructures. The measured propagation time of a pulse is shown in Fig. 4. The microwave pulse has traveled either through air or it has crossed an evanescent barrier [6]. The linewidth of the pulse represents the signal. The experimental result is that the tunneled signal has passed the airborne signal at a superluminal velocity of 4.7c. The measurements of the traversal time are carried out under vacuum-like conditions at the exit of the evanescent region.

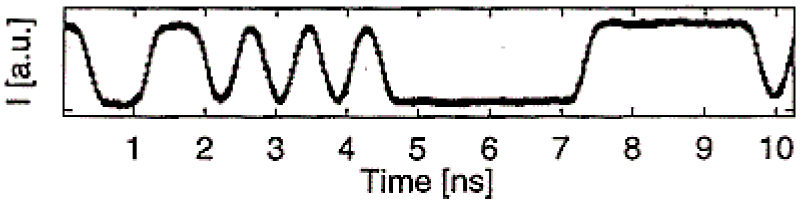


Fig. 3 An example of a modern AM signal used in optoelectronics. The halfwidth of the pulse-like signal represents the number of digits, i.e. the transmitted information. The carrier wave frequency is 2 x 10^14 Hz and the amplitude modulation is limited to a frequency band width of about 10^10 Hz.

4 Some implications of superluminal signal velocity

Measured microwave signals are shown in Fig. 4. The halfwidth (information) of the tunneled signal has traversed the evanescent region at a velocity of 4.7c. As explained above, signals have a limited frequency spectrum since their energy content W is always finite and detectable frequency components with $\omega \geq W/\hbar$ can not exist.

In this experiment all frequency components of the signal are evanescent and move at a velocity faster than c. The beginning of the evanescent signal overtakes that of the airborne signal as seen in Fig. 4. The superluminal velocity of evanescent modes has some interesting features differing fundamentally from luminal or subluminal propagation of waves with real wave numbers. This will be discussed in the following subsections.

4.1 Change of chronological order

The existence of a superluminal signal velocity ensures the possibility of an interchange of chronological order which is established by Radar coordinates. Let us assume an inertial system Sigma 2 moves away from system Sigma 1 with a velocity vr. Special Relativity (SR) gives the following relationship for the travelling time Delta t and for the distance Delta x of a signal in the system Delta I which is watched in Delta II

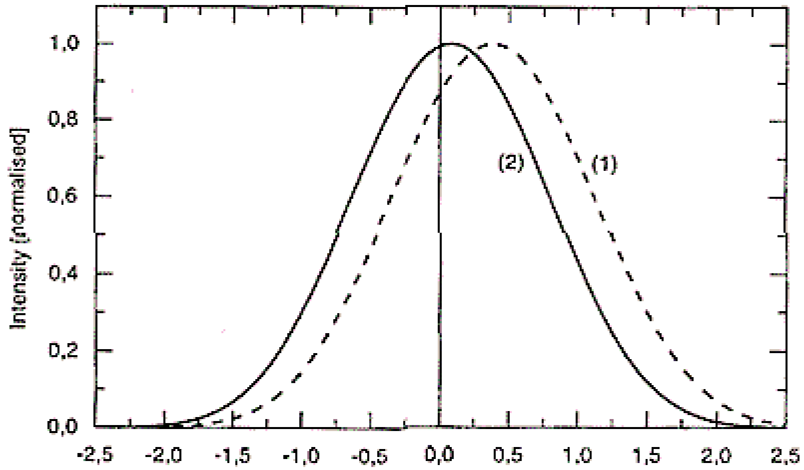
$$\Delta t_{II} = \frac{\Delta t_I - v_r \Delta x_I / c^2}{(1 - v_r^2/c^2)^{1/2}} = \frac{\Delta t_I (1 - v_S v_r / c^2)}{(1 - v_r^2/c^2)^{1/2}}$$

- Equation 2 -

vr larger or equal c^2/vS is the condition for the change of chronological order, i.e. $\Delta t_{II} \leq 0$, between the systems Sigma 1 and Sigma 2. For example, at a signal velocity $v_S \geq 10c$, the chronological order changes at $v_r \leq 0.1c$. This result does not violate SR, since the common constraint $v_S \leq c$ is forced on electromagnetic wave propagation in a dispersive medium and not on the propagation of evanescent modes.

4.2 Negative electromagnetic energy

The Schroedinger equation yields a negative kinetic energy in the tunneling case, since the potential U is larger than the particle's total energy W:



Time [ns]

Fig. 4 Measured barrier traversal time of a microwave packet through a multilayer structure inside a waveguide (barrier length 114.2 mm). The center frequency has been 8.7 GHz with a frequency width of + 0.5 GHz. The pulse's magnitudes are normalized. The slow pulse (1) traversed the empty waveguide, whereas the fast one (2) has tunneled the forbidden gap of the same length. The maximum corresponds to the center of mass and equals the group velocity. The group velocity of the tunneled signal was 4.7c [6]. The transmission dispersion of the barrier is shown in Fig. 1(c) curve b). The tunneled signal (i.e. the halfwidth of the pulse) traversed the 114.2 mm long barrier in 81 picoseconds, whereas the signal spent 380 picoseconds to cross the same distance in air. The time resolution in the experiment has been better than +- 1 picosecond [4,6].

$$\frac{d^2\Psi}{d^2x} + \frac{2m}{\hbar^2}(W-U)\Psi = 0.$$

- Equation 3 -

The same happens to evanescent modes. Within the mathematical analogy, their kinetic electromagnetic energy is negative too. The Helmholtz equation for the electric field E in a waveguide is given by the relationship

$$\frac{d^2E}{d^2x} + (k^2 - k_c^2)E = 0$$

- Equation 4 -

where kc is the cut-off wave number of the evanescent regime. The quantity (k^2 - k^2/c) plays a role analogous to the energy eigenvalue and is negative in the case of evanescent modes.
The dielectric function c of evanescent modes is negative and thus the refractive index is imaginary. For the basic mode a rectangular waveguide has the following dispersion of its dielectric function, where kc = (pi/b)^2 holds and b is the waveguide width,

$$\epsilon(\lambda_0) = (k/k_0)^2 = 1 - (\lambda_0/2b)^2$$

- Equation 5 -

lambda 0 is the free space wavelength of the electromagnetic wave.
In the case of tunneling it is argued that a particle can only be measured in the barrier with a photon having an energy $\hbar\omega \geq (U - W)$ [7]. This means that the total energy of the system is positive. According to Eq. (5), the evanescent mode's electric energy density rho is given by the relationship

$$\rho = \frac{1}{2}\epsilon\epsilon_0 E^2 < 0$$

- Equation 6 -

where epsilon o is the electric permeability of the vacuum.
The analogy between the Schroedinger equation and the Helmholtz equation holds again and it is not possible to measure an evanescent mode. Achim Enders and I tried hard to measure evanescent modes with probes put into the evanescent region but failed. Obviously evanescent modes are not directly measurable in analogy to a particle in a tunnel. We might also say that this problem is due to an impedance mismatch between the evanescent mode and a probe. The impedance Z of the basic mode in a rectangular waveguide is given by the relationship

$$Z = Z_0\ \epsilon^{-1/2}$$

- Equation 7 -

where Z 0 is the free space impedance. In the evanescent regime k < kc the impedance is imaginary.

4.3 The not-causal evanescent region

Evanescent modes do not experience a phase shift inside the evanescent region [2, 3]. They cross this region without consuming time. The predicted [3] and the measured [2] time delay happens at the boundary between the wave and the evanescent mode regime. For opaque barriers (i.e. kappa chi equal or greater than 1, where kappa is the imaginary wave number and chi the length of the evanescent barrier) the phase shift becomes constant with approximately 2 pi which corresponds to one oscillation time of the mode. In fact the measured barrier traversal time was roughly equal to the reciprocal frequency in the microwave as well as in the optical experiments, i.e. either in the 100 ps or in the 2 fs time range independent of the barrier length [2]. The latter behavior is called Hartman effect: the tunneling time is independent of barrier length and has indeed been measured with microwave pulses thirty years after its prediction [5].

5 Summing up

Evanescent modes show some amazing properties which we are not familiar with. For instance, the evanescent region is not causal since evanescent modes do not spend time there. This is an experimental result due to the fact that the traversal time is independent of barrier length.

Another strange experience in classical physics is that evanescent fields cannot be measured. This is due to their negative energy or to the impedance mismatch. Amazingly enough, this is in analogy with wave mechanical tunneling.

The energy of a signal is always finite thus resulting in a limited frequency spectrum according to Planck's energy quantum . This is a fundamental deficiency of classical physics which assumes the measurability of any small amount of energy.
A physical signal never has an ideal front, the latter needs infinite high frequency components with a correspondingly high energy.
Another consequence of the frequency band limitation of signals is, if they have only evanescent mode components, the signal may travel faster than light.
Front, group, signal, and energy velocities all have the same value in vacuum. Bearing in mind the narrow frequency band of signals, the former statement holds also for the velocities of evanescent modes. In first order approximation the dispersion relation of a stop band is constant and a significant pulse reshaping does not take place. This result demonstrates that signals and effects may be transmitted with superluminal velocities provided that they are carried by evanescent modes.

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