Electromagnetic propagation through non-dissipative and dissipative barriers

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Abstract

A Matlab simulation was developed to help visualise and investigate electromagnetic tunnelling through particular non-dissipative and dissipative barriers within a waveguide. The theory behind the simulation is based on a transmission line model that accurately predicts experimental results and is shown to be equivalent to previous numerical and quantum tunnelling models.

A few useful speeds referring to electromagnetic waves have been defined and utilised to calculate the speeds at which different incident time signals penetrate electromagnetic barriers.

Due to bandwidth restrictions, the created incident time signals had wavepacket properties. The importance of resampling an oscillating signal at the appropriate frequency to avoid aliasing has been recognised.

The definition and creation of matched signals that can penetrate long barriers yet remain a single pulse have been investigated. Such signals will have no practical application since the attenuation will deem the transmitted signals immeasurable. However, the speeds through these larger barrier lengths will have a smaller uncertainty since the time delays are longer. Most of the signal distortion depends only on the barrier interfaces rather than the barrier length.

Penetration through dissipative barriers gives speeds below the vacuum speed of light for all barrier lengths investigated. Faster than light speeds are however predicted for penetration through non-dissipative barriers greater than about 4cm.

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Chapter 1

Introduction

1.1 *Tunnelling and the collapse of causality*

Causality allows two different observers to agree on a cause and an effect of a particular event and is a fundamental assumption of modern relativistic physics.

According to Einstein's theory of special relativity, if a signal could travel faster than the speed of light then there would be a violation of causality. Signals would seem to arrive before they departed and they could even appear to travel backwards in time. By making use of superluminal signals it would be possible to communicate with the past, which is not logically possible. To overcome this 'logical disaster' it has been assumed throughout the physics world that no signal may travel faster than c, the speed of light in free space [1]. Speeds greater than c, are defined to be superluminal while speeds less than c are defined to be subluminal.

In recent years, experiments on quantum barrier tunnelling and electromagnetic barrier tunnelling have yielded superluminal speeds creating wide public interest [2, 3]. Experiments in the quantum regime consist of two-photon interferometry [4], or tachyonlike excitations in inverted two level media [5, 6]. Experiments in the electromagnetic regime consist of microwave propagation over short distances using launcher and receiver horns [7], microwave transmission through undersized waveguides [8-11], photonic waveguide/heterostructure tunnelling experiments [12, 13] and more recently total internal reflection in a double prism experiment [14]. Electromagnetic barriers can magnify the time scale up to nanoseconds so microwave experiments can be

compared with theoretical predictions taken from quantum tunnelling which require a less accessible time range [15]. This is because the length of the barrier must be of the order of the wavelength of the radiation for measurable tunnelling to occur. Propagation times in the nanosecond regime can be obtained with microwave barriers (electromagnetic radiation with cm wavelengths).

1.2 *The analogy between quantum and electromagnetic tunnelling*

The analogy between quantum tunnelling and electromagnetic (or photon) tunnelling is well known [16-18]. The analogy is from a similarity between the two fundamental equations governing these seemingly different tunnelling situations. The one dimensional Schrödinger wave equation is the basic relationship for determining wave functions and energy levels of a quantum particle. The time independent Schrödinger equation can be written as

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E-U)\psi = 0 \tag{1.1}$$

Where ψ is the wavefunction, m is the particle mass, $\hbar$ is Planck's constant divided by 2π, E is the particle energy, and U is the uniform potential energy.

The wave equation derived from Maxwell's equations for classical electromagnetic fields is

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t} + \mu\varepsilon\frac{\partial^2 E}{\partial t^2} \tag{1.2}$$

Where μ is the coefficient of permeability of the medium (usually equal to that of free space μ_0), ε is the coefficient of permitivitty of the medium, σ is the conductivity of the medium and in this case, E is the electromagnetic wave function usually a sinusoid of the form $e^{i\omega t-\gamma z}$ where ω is the angular frequency, γ is the complex propagation constant and z is the direction of propagation. If there were no losses (σ =0) then

$$\nabla^2 E = \mu\varepsilon\frac{\partial^2 E}{\partial t^2} \tag{1.3}$$

Doing the differentiation

$$\frac{\partial^2 E}{\partial t^2} = -\omega^2 E \tag{1.4}$$

and substituting in

$$\mu\varepsilon = \frac{n^2}{c^2} \tag{1.5}$$

Where n is the refractive index of the medium and c is the speed of light in a vacuum, Equation (1.3) can be re-written as:

$$\nabla^2 E + \frac{n^2\omega^2}{c^2} E = 0 \tag{1.6}$$

Equations (1.1) and (1.6) are formally identical and if we write:

$$\frac{n^2\omega^2}{c^2} = \frac{2m}{\hbar^2}(E - U) \tag{1.7}$$

Then an electromagnetic wave with frequency ω in a medium with a refractive index of n is analogous to a quantum particle with energy E in a potential U.

Quantum particles are known to 'tunnel' through potential barriers [19-21] and there exist situations where electromagnetic 'tunnelling' also occurs. One situation in the electromagnetic regime where tunnelling occurs is along a waveguide containing a barrier (a region where propagation does not occur). Such a region is said to be evanescent.

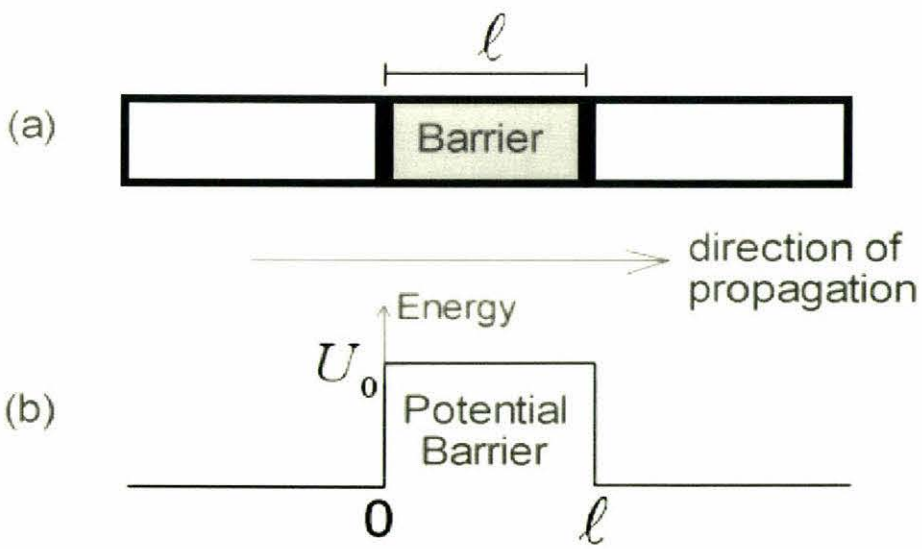

Figure 1.1: Tunnelling analogies. (a) A waveguide with an evanescent barrier of length ℓ. (b) Analogous potential quantum barrier of length ℓ and height U_0.

In this study, the waveguide with a barrier can be considered in 3 sections. It is required that the dominant waveguide mode be freely propagated through the first and third sections, this implies that the signal frequencies f be greater than f_1 (the lower cut-off frequency in regions 1 and 3). It is also required that the dominant mode be evanescent in the second section, this implies that f be less than f_2 (the upper cut-off frequency in region 2), see equation (2.11) in section 2.2.1

1.3 *Tunnelling time and the Hartman effect*

How long does a quantum particle or electromagnetic wave take to tunnel through a barrier region? This question has created much interest and speculation over recent years. In 1962, Thomas E. Hartman published a paper [19] giving analytic expressions for the time spent by a quantum particle tunnelling through a potential barrier. He found that the transmission times were less than the time that would be required for the incident particle to travel a distance equal to the barrier length with speed c. This result leads to a finite tunnelling time that is independent of the barrier length. In the case of electromagnetic tunnelling through a barrier within a waveguide, there is a noticeable time delay. This delay arises from phase changes on transmission through the barrier interfaces and not from the traversal of the barrier. Likewise, studies on the dwell times of a quantum particle tunnelling through a quantum potential barrier have shown that the tunnelling particles spend equal amounts of time near the entrance and exit faces of the barrier, but vanishingly little within the barrier [20, 21]. Because of this, superluminal (faster than light) speeds are predicted for both quantum and electromagnetic tunnelling. Theoretical studies based on the 1-D Klein-Gordon equation show that a Gaussian wavepacket incident on the left side of a barrier, emerges on the right side at an earlier time than would appear to be allowed by causal propagation [22]. It will be shown later in this thesis why a Gaussian signal is the preferred signal to use in such an investigation. The superluminal experiments mentioned in section 1.1 are in accordance with the Hartman effect.

1.4 *Electromagnetic tunnelling through a waveguide*

Throughout the 1990's a group of scientists under the leadership of Günter Nimtz at the University of Cologne carried out 'superluminal' experiments [8-13] using a waveguide with various types of barriers. Their results suggested that for particular barriers, a 'signal' could be sent faster than the speed of light. One of their studies involved the experimental investigation of electromagnetic waveguide tunnelling through both dissipative and non-dissipative barriers [8]. Barrier lengths of 4.9 cm and 6.47 cm were fabricated and the results of this experiment were presented as two graphs, refer to figure 1.2. The first graph showed the modulus of the transmission coefficient as a function of frequency while the second showed the phase shift of the transmission coefficient as a function of frequency. Time domain signals can be constructed from these frequency domain experiments.

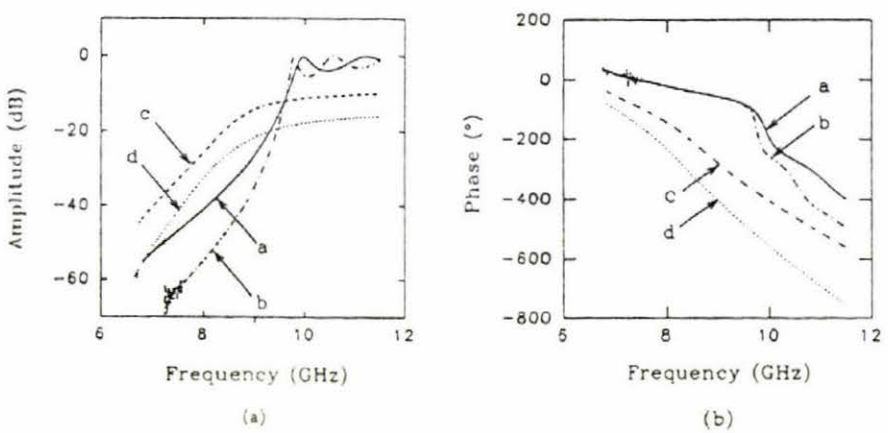

Figure 1.2: Experimental Results. Reproduced from Fig.2, page 1381, Nimtz *et al.* [8]. Transmission coefficient magnitude against frequency (a) and phase against frequency (b) for two barrier lengths a,c=4.9cm and b,d=6.47cm. c and d are filled with a complex dielectric medium.

It was claimed that for the non-dissipative barriers, the traversal time was independent of barrier length resulting in superluminal speeds. The group speeds that were calculated from the phase time for the 7GHz component gave speeds of 1.1c and 1.5c through the 4.9cm and 6.47cm non-dissipative barriers respectively. Their results also showed that with dissipation, the phase shift became dependent on barrier length. The propagation phase change in this case is dominant and the Hartman effect was not observed. Consequently, superluminal speeds were not observed. The group speeds calculated gave speeds of 0.7c for both dissipative barrier lengths (again for the 7GHz component).