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Detection of Superluminal (but Causal) Group Velocity in One-Dimensional Photonic Crystals Using a High Power Microwave Source

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Abstract

A novel time-domain experiment was performed utilizing a high power backward wave oscillator to generate a wave packet whose interaction with the stop band of a one-dimensional photonic crystal (1DPC) was studied. A companion wave packet propagating in free space was observed to arrive measurably later in time than the wave packet incident onto the 1DPC. This result is consistent with special relativity and causality since the frontal velocity of the signal never exceeds the speed of light in vacuum.

Introduction

The subject of superluminal group velocity has received much attention in recent years [1]. The first reference to group velocity dates back to Hamilton [2], and in its modern form was reintroduced by Rayleigh [3]. As early as 1907 it was known that group velocity in regions of anomalous dispersion exceeds c, the speed of light in vacuum. This apparent contradiction with special relativity was studied by Sommerfeld and Brillouin [4]. In their noted work, they showed that, for a step-function input propagating through a Lorentzian gas, the early part of the signal, the so-called "forerunner," always remains luminal. In order to circumvent the aforementioned problem in regions of anomalous dispersion, they arbitrarily defined a new velocity termed "signal velocity." This is the speed at which the half-maximum of the wave travels. From then on, the traditional view has rendered superluminal group velocity either useless, or without any physical significance [4-6].

In 1932 MacColl [7] argued that a transmitted wave packet tunneling through a potential barrier will appear on the other side of the barrier almost instantaneously. Wigner [8] later showed that MacColl's conclusion was incorrect in that there was a finite time delay for the tunneling process. Wigner's analysis indicated that in classical theory this delay or "retardation," expressed in units of distance, must always remain greater than the radius of the scattering potential. However, due to the wave nature of the wave function, the aforementioned inequality "will be violated occasionally." It is precisely these occasional violations that are the subject of interest. A 1962 paper by Hartman [9] rekindled the debate regarding the tunneling time of an electron through a potential barrier. More recently the equivalent problem of photon tunneling (evanescent modes) has received increased attention [10,11]. Similar experiments have been performed using microwaves as well [12,13].

This paper describes the results from a time-domain experiment that was designed to detect the superluminal (but causal) group velocity of a wave packet at X-band. In contrast with the earlier studies at microwave frequencies, the medium that was used was the stop band of a one-dimensional photonic crystal (1DPC) array. It must be emphasized that, in accordance with Einstein causality, the earliest parts of the signals (forerunners) propagated at c.

Experimental Set-up

Figure 1 is the experimental set-up used to compare the time-of-flight for a single microwave pulse (temporally Gaussian wave packet) tunneling through a 1DPC compared with a companion wave packet propagating in free space. In this experiment, a novel frequency-tunable high power microwave source, the Sinus-6 accelerator-driven backward wave oscillator (BWO) [14] was used to generate the single microwave pulse at 100s MW peak power. Since the output of this source is the TM_{01} mode of a circular waveguide, a mode convertor (MC) [15] was placed on the source just prior to the conical horn antenna (CHA) in order to radiate a TE_{11} spatially Gaussian-like mode distribution.

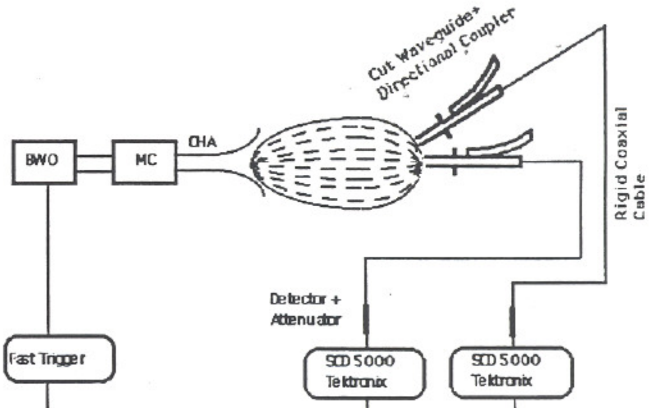

Figure 1. Experimental set-up for detecting the difference between the propagation time of a Gaussian wave packet in free space compared with a companion wave packet incident upon the stop band of a 1DPC.

The frequency output of the source was tuned to generate 10 ns duration wave packets at 9.68 GHz (Δf=100 MHz). Using an open-ended waveguide and a directional coupler, microwave power at two different points of the CHA radiation pattern were sampled. In order to measure the relative time delay between the two paths ("center" and "side") due to different cable lengths, internal differences of the two pulse monitoring oscilloscopes (Tektronix SCD 5000), *etc.*, a series of wave packets was generated. The resultant delay was electronically "removed" such that the peaks corresponding to the pulses traveling through "center-path" and "side-path" in the absence of the 1DPC coincided.

Experimental Results and Analysis

A 1DPC of alternating layers of polycarbonate and air, designed to have minimal dispersion at 9.68 GHz, was inserted in the "center-path" indicated in Fig. 1. The results of the average of several pulses propagating through free space and a companion wave packet propagating through the 1DPC are shown in Fig. 2. The peak of the pulse tunneling through the 1DPC (dotted line) is clearly shifted to an earlier time compared to the free space pulse (solid line). Since group velocity is the velocity by which the peak of a wave packet travels, it is evident that the tunneling pulse propagated superluminally. The measured advance in Fig. 2 is 440 ps, corresponding to a velocity of 2.4 *c*.

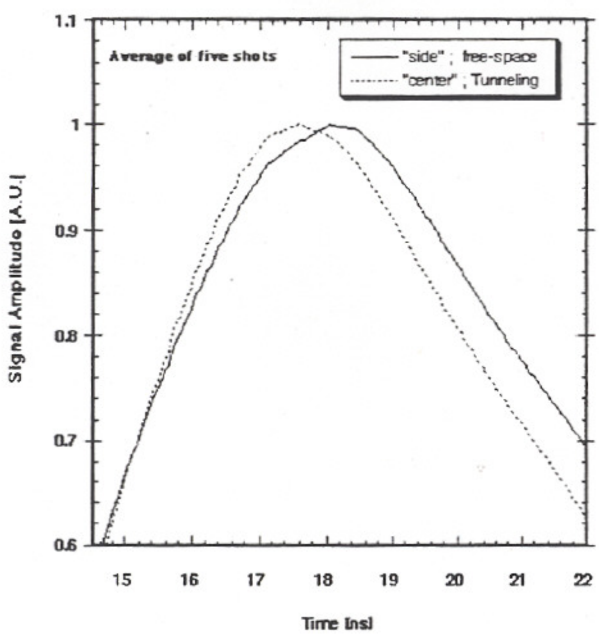

Figure 2. Comparison of the arrival time of a wave packet tunneling through the stop band of a 1DPC (dotted line) and a companion wave packet propagating through free space (solid line).

In this study, it was important to ensure that the pulse tunneling through the center-path did not disperse to the extent that rendered the comparison meaningless. To investigate this, a series of wave packets was launched through the "center-path" both with and without the 1DPC, and the conclusion was that the wave packet suffered minimal dispersion upon tunneling through the 1DPC.

Finally, regarding relativistic causality, although, it is possible to provide a detailed quantitative description [1], here a simplified qualitative explanation is given. It has been shown that there is no causal relation between the peak of the incident wave packet and the transmitted wave [16]. In other words, there is no extra information in the peak of the analytic wave packet that is not already present in the very early part of the signal. In fact, given the function and its derivatives at an earlier point, with the help of analytic continuation, one can extrapolate to all later times. This means that under no circumstances does the "signal" (information) propagate superluminally.

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