SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-2000)

"Bridging the Future-Space Station and Beyond"

January 30-February 3, 2000

Albuquerque, NM

Cosponsored by:

THE BOEING COMPANY

LOCKHEED MARTIN CORPORATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Headquarters, and Field Centers

UNITED STATES DEPARTMENT OF ENERGY
Headquarters
Los Alamos National Laboratories
Sandia National Laboratory

In cooperation with:

AMERICAN ASTRONAUTICAL SOCIETY

AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS,
National & Local Sections

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS
Heat Transfer and Energy Conversion Division

AMERICAN NUCLEAR SOCIETY, Trinity Section

AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Nuclear Engineering Division & Heat Transfer Division

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
Nuclear and Plasma Sciences Society

INTERNATIONAL ASTRONAUTICAL FEDERATION

NASA NATIONAL SPACE GRANT COLLEGE AND FELLOWSHIP PROGRAM
New Mexico Space Grant Consortium

STAIF-2000
FINAL PROGRAM AND ABSTRACT BOOK

Frequency- and Time-Domain Detection of Superluminal Group Velocities in One Dimensional Photonic Crystals (1DPC)

Mohammad Mojahedi[1], Kevin J. Malloy[1] and Raymond Chiao[2]

[1]*Center for High Technology Materials (CHTM), 1313 Goddard SE, Albuquerque NM 87106*
[2]*Department of physics, University of California at Berkeley, Berkeley CA 94720*

email: mojahed@chtm.unm.edu; malloy@chtm.unm.edu; chiao@physics.berkeley.edu

Abstract. In this work we discuss two recent experiments in the frequency- and time-domain for electromagnetic waves tunneling through an optical multilayer also known as 1DPC. These experiments are intended to demonstrate measurability and hence the physical reality of the superluminal (exceeding the speed of light in vacuum) group velocities for evanescent modes. Despite these anomalous velocities, Einstein causality is not violated since the front (Sommerfeld forerunner) remains luminal.

Frequency- and Time-Domain Detection of Superluminal Group Velocities in One Dimensional Photonic Crystals (1DPC)

Mohammad Mojahedi[1], Kevin J. Malloy[1] and Raymond Chiao[2]

[1]*Center for High Technology Materials (CHTM), 1313 Goddard SE, Albuquerque NM 87106*
[2]*Department of physics, University of California at Berkeley, Berkeley CA 94720*

email: *mojahed@chtm.unm.edu; malloy@chtm.unm.edu; chiao@physics.berkeley.edu*

Abstract. In this work we discuss two recent experiments in the frequency- and time-domain for electromagnetic waves tunneling through an optical multilayer also known as 1DPC. These experiments are intended to demonstrate measurability and hence the physical reality of the superluminal (exceeding the speed of light in vacuum) group velocities for evanescent modes. Despite these anomalous velocities, Einstein causality is not violated since the front (Sommerfeld forerunner) remains luminal.

SUPERLUMINALITY AND BREAKTHROUGH PROULSION PHYSICS (BPP) PROGRAM GOALS

In recent years, the subject of superluminal propagation has received much attention. A review of this field is provided in reference (Chiao, 1997) and a short summary will be given in the next section. Unfortunately, as is the case with any new subject, there are misinterpretations and misrepresentations which deserve a closer examinations. For example it has been suggested that superluminal group velocity is indeed the information velocity (Heitmann, 1994) and concepts such as Sommerfeld forerunner are irrelevant, or that evanescent modes are not necessarily Einstein causal (Nimtz, 1999). Aside from these controversies, the BPP program has challenged researchers with the need to attain the ultimate transit speed to dramatically reduce travel times. In this regard, the possibility of superluminal velocities and the role of the Sommerfeld forerunner (or the front) deserve much attention. If the measured superluminal group velocities are indeed the information velocity, then one must conclude that Einstein causality has been violated. On the other hand, if as we believe the critical concept is the propagation of the Sommerfeld forerunner, which under all circumstances shall remain luminal, then there is no violation of special relativity. The issue of superluminal propagation and Sommerfeld forerunner and their connection with the well known requirements of special relativity is closely associated with the BPP "maximum transit speeds" goal and in particular they relate to critical "make-or-break issues".

INTRODUCTION TO SUPERLUMINAL PROPAGATION

Chiao and his co-workers (Steinberg, 1993) have demonstrated that single photons generated in the process of spontaneous parametric down-conversion can tunnel through an optical multilayer with group velocities 1.7 times faster than *c*. Additionally, in a series of experiments Ranfagni and his coworkers have used undersized waveguides, slightly misaligned horn antennas and two side-by side prisms (resulting in frustrated total internal reflection) to demonstrated superluminal velocities (Ranfagni, 1991a; Ranfagni, 1991b; Ranfagni, 1993; Mugnai, 1998). Nimtz and his coworkers have also studied the undersized waveguide and were able to improve on Ranfagni's results (Enders, 1992; Enders, 1993a; Enders, 1993b; Nimtz, 1994; Nimtz, 1997). They (Nimtz) also briefly considered tunneling through an optical multilayer inserted in an undersized waveguide (Nimtz, 1994). Unfortunately, this experiment in particular, and their interpretation in general, is incomplete. For example, to assign the superluminal tunneling time to the 1DPC is misleading since by their own admission the tunneling is due to both the undersized waveguide and the 1DPC. Moreover, in Refs. (Nimtz, 1994), and in fact in all of their frequency-domain analysis, they used the Fourier transform to extend the frequency-domain network analyzer (NA) results to the time-domain. In their use of the Fourier integral, they had to replace the $-\infty$ to $+\infty$ limits of the integral with the bounded limit of ν_1 to ν_2. This meant that their *assumed* incident wave packet had zero frequency components outside (ν_1, ν_2) frequency interval [8.7±0.5 GHz in their particular case (Nimtz, 1994)]. This simple point can lead to misinterpretation when presenting frequency-domain results as direct time-domain measurements, particularly in light of the fact that these neglected large frequency components are essential in understanding the Sommerfeld forerunner. Even more troubling, in their analysis they only used the transmission function *amplitude* to calculate the time-domain signal. This is equivalent to assuming a *constant phase* for the transmission function, which is strictly true only for an infinitely long, undersized waveguide or 1DPC, and in fact is erroneous in the case of the 1DPC with few periods. In this light, a correct and reliable measurement of the tunneling times and superluminal group velocities for 1DPCs in the microwave region is in order.

Before closing this section, let us briefly discuss the previous understanding of evanescent wave propagation and electromagnetic wave tunneling. Historically, evanescent propagation of the tunneling wave packet was thought to distort the transmitted pulse to the extent that the known theoretical superluminal or even negative group velocities were rendered unphysical or meaningless (Brillouin 1960) (Landau, 1984) (Born, 1970) (Brillouin, 1946) (Jackson, 1975). However, most recently this trend is beginning to change as evidenced by the latest edition of "Classical Electrodynamics" by John Jackson (Jackson, 1998) or the review paper by Chiao and Steinberg in E. Wolf "*Progress in optics*" (Chiao, 1997).

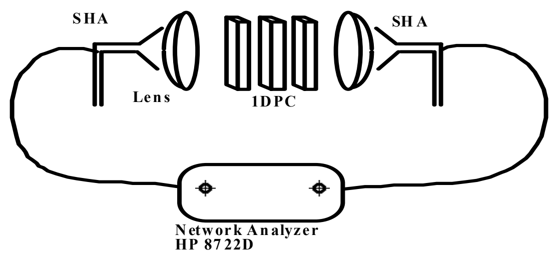

FIGURE 1. Frequency-domain experimental setup.

DESCRIPTION OF THE EXPERIMENTAL PROCEDURES

Figure 1 shows the free-space experimental setup. It consists of two K-band standard horn antennas (SHA), connected to ports 1 and 2 of an HP 8722D NA, configured to measure the transmission coefficient. The setup is enclosed in a anechoic chamber to reduce stray signals.

With recent advances in non-coaxial (free-space) calibration techniques for NA such as the "Thru-Line-Reflect" (TRL), it is possible to remove most of the systematic errors and the influence of the microwave components on the measured transmission coefficient. Performing the TRL calibration in free-space allows us to measure the transmission coefficient ($T = |T| e^{-i\varphi}$) solely due to the 1DPC and eliminates dispersion and dissipation losses associated with inserting the 1DPC inside a waveguide. After calibrating the system (without the 1DPC), a reference plane of unit magnitude for $|T|$ and zero phase for φ is established midway between the two SHAs. At this point, the 1DPC is inserted and the receiver horn is moved back exactly by a length equal to the thickness of the 1DPC (L_{pc}).

Within the stationary phase approximation, the concept of group delay, given by the angular-frequency derivative of the transmission phase ($-\partial \varphi / \partial \omega$), is a natural approach to understanding propagation through a finite, dispersive structure. This concept can be extended in order to obtain the group velocity as a function of frequency, according to;

$$\frac{v_g}{c} = \frac{L_{pc}}{c\,\tau_g} = \frac{-L_{pc}}{c\left(\partial\varphi / \partial\omega\right)}. \tag{1}$$

Figure 2 is the calculated (solid line) and measured (dotted line) unwrapped phase for a 1DPC with three,

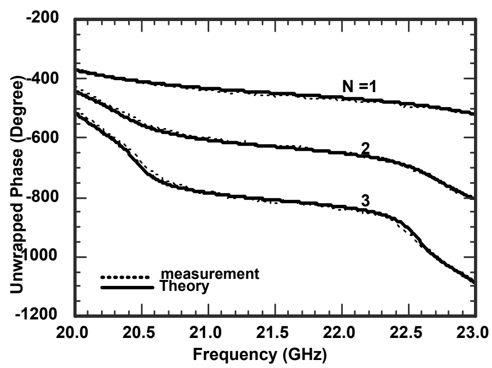

FIGURE 2. Theoretical and measured phase.

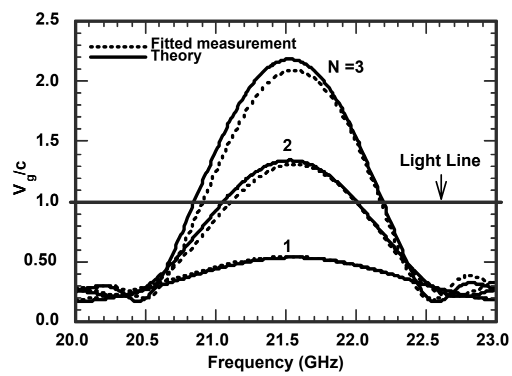

FIGURE 3. Normalized group velocity.

two and one dielectric slabs (the spacer is always air). The theoretical calculation is based on the diagonalization of one period matrix, and is presented in Ref. (Mojahedi, 1999), as space limitations prevent our repeating it here.

According to Eq. (1), the data presented in Fig. (2) must be differentiated with respect to frequency. However, applying differentiation to noisy data amplifies the noise and may lead to spurious effects. To avoid the arbitrariness associated with smoothing the data, we have chosen to obtain the best nonlinear least square fit of the experimental phase data to the equation for the transmission phase (φ) presented in Ref. (Mojahedi, 1999). The parameters used in this fit are the dielectric thickness (d_j), spacer thickness (d_i) and the real part of the index of refraction (n'_j). Figure 3 shows the result of the least square fit to the phase data of Fig. 2 together with applying Eq. (1), in order to determine the normalized group velocity in a 1DPC with one, two, and three dielectric slabs.

Along with the velocities derived from the fit (dotted curves), the theoretical group velocities calculated from measured values of the thicknesses and indices are also shown (solid curves). The fitting parameters and the measured values for these parameters are shown in Table 1. As Fig. 3 indicates, in the case of N=3, a maximum superluminal group velocity 2.1 times c is observed.

TABLE 1. Measured and fitted parameters for the 1DPC with Eccostock® slab and air spacer.

	Fitting, $N=3$	**Fitting, $N=2$**	**Fitting, $N=1$**	**Measured**
d_i	1.794 cm	1.825 cm	———	1.76 cm
d_j	1.399 cm	1.366 cm	1.396 cm	1.33 cm
n'_j	3.216	3.288	3.245	3.40

Superluminal tunneling can also be directly demonstrated in the time-domain. Figure 4 is the experimental setup used to compare the time-of-flight for a single microwave pulse tunneling through a 1DPC as compared with a companion wave packet propagating in free space. A backward-wave-oscillator (BWO) in conjunction with a conical horn antenna (CHA) is used to generate a narrow single-microwave pulse

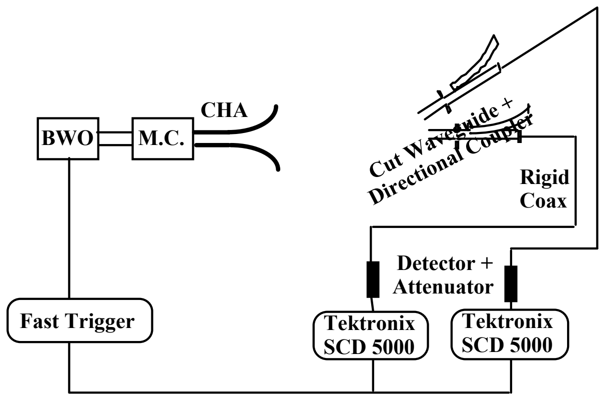

FIGURE 4. Time-domain Experimental setup.

centered at 9.68 GHz (100 MHz bandwidth) of approximately 10 ns duration. The microwave pulse is sampled at two distinct points of the antenna's radiation intensity pattern, hereon referred to as "side" and "center". The delay between these two paths due to different cable lengths, internal differences of the

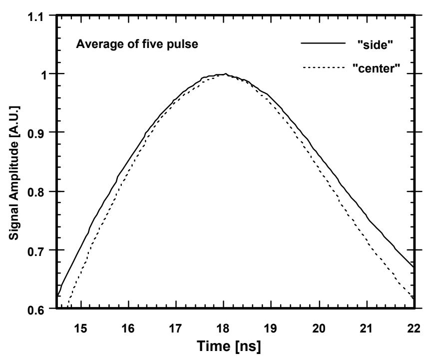

FIGURE 5. Reference Pulses.

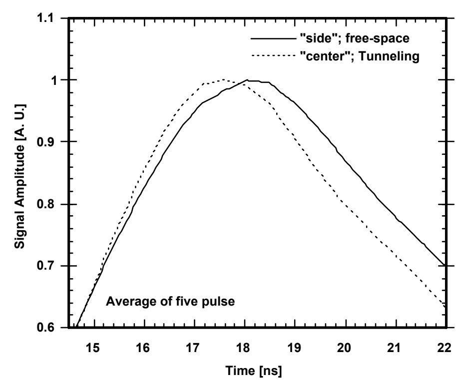

FIGURE 6. Shift to earlier times.

scopes' display units (Tektronix SCD-5000), or any other mechanism was measured in the absence of the 1DPC. This delay was then removed electronically such that the peaks of the two "side" and "center" pulses arrive at the same time. Figure 5 shows the result. At this point, a 1DPC consisting of alternating layers of polycarbonate and air, designed to have minimal dispersion at 9.68 GHz, was inserted in the "center" path. The results are depicted in Fig. 6.

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. 6 is 440 ± 20 ps, corresponding to a velocity of (2.38 ± 0.15) *c*.

The traditional view asserts that the tunneling wave packet is distorted to the extent that the comparison between the incident and transmitted wave packet is rendered meaningless (Brillouin, 1960, pp. 22) (Landau, 1984). Therefore, it is important to compare the transmitted tunneling pulse with the incident pulse propagating along the same path. Repeated measurements indicated that the FWHM of the "center" tunneling pulse depicted in Fig. 6 is only increased by 2.2% as compared to the "center" free-space pulse depicted in Fig. 5 (Mojahedi, 1999, pp. 41). In light of this, one must accept the fact that if group velocity is a good parameter describing the propagation of a free-space wave packet, it must also be a good variable describing the propagation of the tunneling wave packet.

WHY EINSTEIN CAUSALITY IS NOT VILOATED

At this point the reader may ask: How are the results presented in the last section are in agreement with Einstein causality? The answer to this question rests in the fact that under all circumstances the velocity by which the front or the Sommerfeld forerunner travels remains luminal. This compels us to associate the information velocity with the velocity of these points of non-analyticity (Chiao, 1997). This idea, although in complete agreement with our understanding of theory of special relativity and electromagnetism, is perhaps not a practical definition under all circumstances. The reason lies in the fact that the forerunner's field is usually of very high frequency and very small amplitude.

It must be emphasized that at the observation point x, no detection of the signal (the front) can be made prior to time x/c. This can be seen via contour integration, in the upper half plane, of the expressions such as Eq. (2) below, which describes the field at the position x and the time t for a medium with index or effective index n (Jackson, 1998, pp. 336)

$$u(x,t) = \int_{-\infty}^{+\infty} \frac{2}{1+n(\omega)} A(\omega)\, e^{i k(\omega) x - i \omega t}\, d\omega\,, \tag{2}$$

$$A(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} u(x=0,t)\; e^{i \omega t}\; d\omega\,. \tag{3}$$

At the time $t = t_0 = x/c$ the earliest part of the signal (Sommerfeld forerunner) can be detected. The frequency of oscillation and the field amplitude for these forerunner's fields are discussed in Ref. (Mojahedi, 1999, pp. 60-69). To summarize those results, the frequency of oscillation is given by

$$\omega_s = \sqrt{G'(0)} \Bigg/ \sqrt{2\left(\frac{t}{t_0} - 1\right)}\,, \tag{4}$$

where $G'(0)$ is the time derivative of the susceptibility kernel (Jackson 1998, pp. 332) evaluated at $t = 0$. Furthermore, for the incident wavepackets proportional to t^m (m is an integer) the Sommerfeld forerunner is described by a Bessel function of order m according to

$$u(x,t) \approx a \left(\frac{t - t_0}{\gamma}\right)^{m/2} J_m\left(2\sqrt{\gamma\,(t - t_0)}\right); \qquad \gamma = \frac{G'(0)\,t_0}{2}\,; \qquad for\; t > t_0\,. \tag{5}$$

In light of importance of the Sommerfeld forerunner and its connection to Einstein causality, we are currently in the process of devising a procedure which allows experimental detection of this and the Brillouin forerunner for a 1DPC.

CONCLUSIONS

In this manuscript we have discussed frequency- and time- domain experiments which demonstrate superluminal group velocities. Unfortunately, the response to such phenomenon has been from two opposite points of view. While traditionally it has been believed that superluminal group velocities are unphysical (see the references in the text) the experiments presented here along with many others cited in the text have demonstrated the measurability and hence the physical reality of such abnormal behavior. On the other hand some authors have argued that evanescent modes used in these experiments are not necessarily Einstein causal and that the measured superluminal group velocities are indeed information velocities and that the notion of the front (Sommerfeld forerunner), which must remain luminal under all circumstances, is not relevant. Clearly, such assertions (if true) can result in violation of special relativity, which requires the speed of light in vacuum to be the ultimate information velocity.

In this work in addition to presenting two experiment which demonstrate superluminal (but Einstein causal) group velocities, we have discussed the role, the frequency, and the functional form of the Sommerfeld forerunner. Currently, within the NASA-BPP program we are investigating the experimental conditions under which the theoretical predictions regarding Sommerfeld forerunner can be tested for optical barriers. The subject of superluminal velocity and whether or not this is a genuine information velocity (in violation of Einstein causality) is closely related to BPP challenges set forth as “Discovering methods for achieving the shortest possible travel times,” and is “aimed to advance physics to address critical unknowns, make-or-break issues, or curious effects.”

ACKNOWLEDGMENTS

This material is based on work supported by, or in part, by the US Army Research Office under grant number DAAH04-96-1-0439.

REFERENCES

Born, M. and Wolf, E. *Principles of optics; electromagnetic theory of propagation, interference and diffraction of light*, Oxford, Pergamon, 1970, pp. 23.

Brillouin, L., *Wave propagation in periodic structures; electric filters and crystal lattices*, New York, McGraw-Hill, 1946, pp.75.

Brillouin, L., *Wave propagation and group velocity*, New York, Academic Press, 1960, pp. 74-79.

Chiao, R. Y., and Steinberg, A.M., “Tunneling Times and Superluminality,” *Prog. Optics* **37**, 345-405 (1997).

Enders, A., and Nimtz., G., “On Superluminal Barrier Traversal,” *J. Phys. I France* **2**, 1693-1698 (1992).

Enders, A., and Nimtz, G., “Photonic-Tunneling Experiments,” *Phys. Rev. B* **47**, 9605-9609 (1993).

Enders, A., and Nimtz, G., “Zero-Time Tunneling of Evanescent Mode Packets.” *J. Phys. I France* **3**, 1089-1092 (1993).

Heitmann, W., and Nimtz, G., “On Causality Proofs of Superluminal Barrier Traversal of Frequency Band-Limited Wave-Packets,” *Phys. Lett. A* **196**, 154-158 (1994).

Jackson, J. D., *Classical electrodynamics*, New York, Wiley, 1975, pp. 302.

Jackson, J. D., *Classical electrodynamics*, New York, Wiley, 1998, pp. 325-326.

Landau, L. D., Lifshittz, E. M., et al. *Electrodynamics of continuous media*, Oxford, Pergamon, pp. 285 (1984).

Mojahedi, M., *Superluminal group velocities and structural dispersion*, Albuquerque, University of New Mexico, 1999, pp. 16.

Mugnai, D., Ranfagni, A., et al. “The Question of Tunneling Time Duration : a New Experimental Test At Microwave Scale,” *Phys. Lett. A* **247**, 281-286 (1998).

Nimtz, G., “Evanescent modes are not necessarily Einstein causal,” *Eur. Phys. J. B* **7**, 523-525 (1999).

Nimtz, G., Enders, A., et al. “Photonic Tunneling Times,” *J. Phys. I France* **4**, 565-570 (1994).

Nimtz, G., and Heitmann,W., “Superluminal Photonic Tunneling and Quantum-Electronics,” *Prog. Quant. Electr.* **21**, 81-108 (1997).

Ranfagni, A., Fabeni, P., et al. “Anomalous Pulse Delay in Microwave Propagation : a Plausible Connection to the Tunneling Time,” *Phys. Rev. E* **48**, 1453-1460 (1993).

Ranfagni, A., Mugnai, D., et al. “Delay-Time Measurements in Narrowed Wave-Guides As a Test of Tunneling,” *Appl. Phys. Lett.* **58**, 774-776 (1991).

Ranfagni, A., Mugnai, D., et al. “Optical-Tunneling Time Measures : a Microwave Model,” *Physica B* **175**, 283-286 (1991).

Steinberg, A. M., Kwiat, P. G., et al., “Measurement of the single-photon tunneling time,” *Phys. Rev. Lett.* **71**, 708-711 (1993).