Comments on "Rapid Pulsed Microwave Propagation"

Ádám Tichy-Rács, *Member, IEEE*

In [1], there is a statement about an "experimental observation," which "shows that the leading edge of the pulse modulated microwaves propagates with the velocity $c/\cos\theta$ in a direction θ in open space. Only when θ was chosen to be 0, it was c." If this were correct, it would be a discovery of great importance.

However, there are smaller ignorances, which seem to decrease the importance of the revelation. The authors presented a precise description of the circumstances of their experiment. Their "klystron producing microwave of 8.202 GHz was modulated externally through a pulse generator." Later on, all the calculations refer to signals of the carrier frequency, they neglect the effect of the pulse modulation. Pulses with really short rise times create wide spectrum of generated signals. According to the Hughens principle of wave propagation, the very first wavefront propagates in the waveguide with the velocity of 3×10^8 m/s. Under the conditions of the experiment, a transit time of 5.53 ns is needed for the transmission of the leading edge. This result is much closer to the observation, than the 9.26 ns, which was expected calculating with the group velocity. Behind the first wavefront a special propagation mode, called TE_{01}, and not TEM as indicated in the letter, is building up. The energy of the continuous wave of 8.202-GHz radiation propagates with the group velocity, with 1.791×10^8 m/s. In the case of the 50-ns pulse, most of the energy is transmitted with the group velocity, a small portion propagates faster, a small portion of the whole energy is transmitted slower. The pulse becomes wider even if the results "do not show visible disintegration of the pulse in the range of PRR and pulse rise time tested." Rise time of 22 ns and pulse duration of 50 ns are really not short enough to produce "visible disintegration" during nanoseconds.

In the "tramission through air" experiment, both the phase velocity and the group velocity should be equal to the "intrinsic velocity" 3×10^8 m/s, because the velocity of propagation is independent of the frequency. To speak about phase and group velocities as different quantites has no sense. The mode of propagation is really TEM in the open air, but it is TE_{01} in the waveguide portion. The experimental data shown in Fig. 4 of the paper discussed here correspond to a plane wave propagation mode, but the source of waves is not a plane. The results of the measurement are as constant and as stange as if a crosstalk from one connector to the other were measured. I propose to check, what happens, if the open end of the waveguide as a transmitter radiator is tilted toward the receiver in the offset position. The roles of the receivers in the different positions are changed. The longer path corresponds to the face to face direction and the shorter one corresponds to that θ direction. I propose also to repeat the experiment with the same directions and with different distances.

To sum up, the letter claims, that the measurements show faster propagation, than the velocity of light c. Contrary to the authors conclusion, while there was no meaningful disintegration of the pulse, if the leading edge is transmitted with the phase velocity, the whole pulse was transmitted with that velocity. Even if the original statement were right, all our knowledge should be revised, from the fundamentals of electromagnetic theory up to the theory of relativity. A revelation of such an importance should be received with strong criticism. Before launching, it needs rigorous control on behalf of the authors, on behalf the editors and on behalf the scientific community.

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Response to Á. Tichy-Rács' "Comments on 'Rapid Pulsed Microwave Propagation'"

George C. Giakos and T. Koryu Ishii, *Senior Member, IEEE*

***Abstract*—The authors respond to all technical points raised by Tichy-Rács on the authors' letter "Rapid Pulsed Microwave Propagation." The authors defend their experimental observations.**

It came to the authors' attention that the authors' work [1] has been commented by Á. Tichy-Rács [2]. The authors offer the following responses.

The comment-writer states, "...they neglect the effect of the pulse modulation." He admits later that "Rise time of 22 ns and pulse duration of 50 ns are really not short enough to produce 'visible disintegration' during nanoseconds." This is about the dispersion. The pulse repetition rate of 147 KPPS for 8.202 GHz will not produce discernible dispersion in any indoor-distance of propagation. Anyway, the dispersion is not the issue of the "rapid propagation" [1].

The comment-writer states, "According to the Hughens principle of wave propagation, the very first wavefront propagates in the waveguide with the velocity of 3×10^8 m/s." The Hughens *original* principle *assumes* TEM mode only. Neither microwaves nor *non-TEM mode* was discovered at the time of Hughens. It is a well-established fact that a metallic hollow waveguide cannot support the TEM mode [3]–[7]. The probes employed in the authors work detects TE_{01} mode field in the waveguide. The first pickup antenna probe to observe the transmitter pulsed microwave is inserted 75 cm (12.46 wavelengths) from the transmitter Klystron antenna probe [8]. Therefore, TE_{01} mode is well established by the time the radiated pulsed microwaves reach the first probe, which is the transmitter probe. Therefore, from this point on down the waveguide to the receiving end detector, the mode of propagation is TE_{01} mode and there will be no genuine TEM mode. For the same reason, the comment-writer's statement, "Behind the first wavefront a special propagation mode called TE_{01}, and not TEM as indicated in the paper, is building up," is incorrect. There is neither theoretical work, nor experimental observation to support the comment-writer's statement. Besides, this statement claiming two groups of waves is in conflict with the following his own statement that claims three groups of waves. The comment-writer states, "In the case of the 50 ns pulse, most of the energy is transmitted with the group velocity, a small portion propagates faster, a small portion of the whole energy is transmitted slower." This comment-writer's statement is not supported by either theory or experimental observation. At any

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rate, the whole pulse propagation is not the main issue of the authors' work. The main issue is the speed of propagation of the leading edge of pusled microwaves [8].

The comment-writer states, "The pulse becomes wider even if the results 'do not show visible disintegration of the pulse in the range of PRR and pusle rise time tested.'" Again, in the authors' work [1], the affect of dispersion is negligibly small and the comment-writer's statement is "academic."

The comment-writer states, "In the 'transmission through air' experiment both the phase velocity and the group velocity should be equal to the 'intrinsic velocity' 3×10^8 m/s..." That is true only for the TEM mode propagation. In the direction, angle θ off-axis of TEM mode propagation, the same wave produces longitudinal component of magnetic fields in that off-set direction. Therefore, in that particular direction of interest, the mode of propagation is no longer TEM-mode [3]–[9]. This comment-writer's statement contradicts also to general treatment of plane wave propagation by a number of authors [3], [5], [6], [9], where the apparent phase velocity and the group velocity are different depending on the direction of observation. Therefore, the comment writer's statement is not applicable to the observation in the off axis direction.

The comment-writer states, "...because the velocity of propagation is independent of the frequency. To speak about phase and group velocities as different quantities has no sense." The fact that the velocity of propagation is independent of the frequency means that the medium is nondispersive. The nondispersive medium does not guarantee that the phase velocity and the group velocity are equal to each other. In fact, generally they are not as clearly seen from widely accepted literature [3], [6], [9].

The comment-writer states, "the results of the measurement are as constant and as strange as if a crosstalk from one connector to the other were measured." Prior to sending the authors' work [1] for publication, the presence of the crosstalk and direct interference between the transmitter system and the receiver system were examined many times not only by the authors but also by a number of qualified visitors to the authors' experimental set-ups. Neither the crosstalk, nor the direct interference was found.

The comment-writer states, "I propose to check, what happens if the open end of the waveguide as a transmitter radiator is tilted toward the receiver in the offset position." It had been checked already [8]. As soon as it was done, the situation was no longer offset position. Therefore, the speed of propagation is 3×10^8 m/s [8]. The original face to face direction is now the offset direction and in that direction the speed is $c/\cos\theta$ within a limited range of the offset angle θ [8].

The comment-writer states, "I propose also to repeat the experiment with the same directions and with different distances." The authors have already done so [8] and similar results presented in the letter [1] have been observed repeatedly [8]. In a limited space allowed in the letter [1], only few examples could be presented.

The comment-writer states, "contrary to the authors conclusion..." The authors do not see any contradiction to the authors' conclusion.

The rest of the comment-writer's statements are arbitrary in nature. Therefore, there will be no scientific value for discussion.

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Comments on "Rapid Pulsed Microwave Propagation"

Paul G. Steffes, *Senior Member, IEEE* and
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***Abstract*—A recent letter by Giakos and Ishii and a nearly identical previous paper by Ishii and Giakos claim to have developed conclusive laboratory evidence that demonstrates microwave pulse propagation in waveguides, and in air, at velocities exceeding *c* (the free space speed of light). The authors conclude that it is possible to propagate both energy and information in a non-TEM waveguiding medium at the phase velocity, which often exceeds *c*. Careful analysis of the results presented show several significant potential sources of error, affecting the laboratory results and their interpretation. It is concluded that no credible evidence has been presented demonstrating pulse propagation at velocities exceeding *c*, but that by using carefully calibrated laboratory techniques, highly accurate measurements of pulse propagation velocities are possible.**

I. INTRODUCTION

A recent letter in IEEE MICROWAVE AND GUIDED WAVE LETTERS by Giakos and Ishii [1] and a nearly identical paper published previously in *Microwaves and RF* by Ishii and Giakos [2] purports to show conclusive laboratory evidence of microwave pulse propagation velocities exceeding *c* (the speed of light in free space), both in waveguides and for non-TEM waves propagating in air. The authors concluded that it is possible to propagate both energy and information at the phase velocities which often exceed *c*. Careful analysis of the results presented show several significant potential sources of error, affecting the laboratory results and their interpretation. We conclude that no credible evidence has been presented demonstrating pulse propagation at velocities exceeding *c*, but that by using carefully calibrated laboratory techniques, highly accurate measurements of pulse propagation velocities are possible.

II. REVIEW OF EXPERIMENTS

The two laboratory measurements described consisted of measurements of the propagation delay of pulse modulated microwave carriers in a waveguide and between two antenna horns.

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A. Waveguide Experiment

In their waveguide experiment, the authors used a pulse generator to modulate a klystron operating at 8.202 GHz. The output of the pulse generator was also fed to an HP 1415A time domain reflectometer (TDR), as a sweep trigger. Two microwave detectors were placed in the waveguide: one near the klystron, and another 1.658 farther distant. No description of the detectors is given (one is referred to as the transmitter tunable probe detector), but it is clear from photographs that they are not identical since one has a positive polarity output, and the other has a negative output. The detected pulses were then fed to the TDR for display, triggered by the pulse generator. As detected, the pulses appeared to have a 22–ns rise time with a pulse duration of 50 ns.

In order to measure the propagation delay, the relative time between the trigger pulse and the detected pulse was firt measured for the detector nearest the generator, and then the detector cable was disconnected and reconnected to the second detector and the same measurement was made. The difference in the times measured represented the propagation time, and the authors report a propagation time of 3.30 ns, which corresponds to propagation velocity of 5.0245 x 10^8 m/s. The authors indicate that the accuracy of the measured propagation time was better than 0.05 ns, which corresponds to the accuracy of the TDR [3]. However, they failed to mention the significant uncertainty that results from variation in detector response times.

The reported 22–ns pulse rise time includes the rise time of the waveguide detectors. Typically, such detectors have rise times on the order of 1–200 ns (depending on load impedance), which may vary by factors of 2 or more from one detector to another when manufactured (see e.g., [4]). Even when "matched" detectors are obtained, their response times vary significantly with the power level of the incident carrier [4]. Thus, the response from identical detectors will depend somewhat on their position in the waveguide, and in the case of the free space measurement, the pulse response times will vary dramatically depending on the positioning of the detectors. In general, it is very dificult to measure differential time delays when the accuracies required are a small portion (less than 10%) of the pulse rise times, but for the case where the pulse rise times are not identical, the ability to measure differential delays is dramatically degraded and for this example, accuracies of no better than +5 ns could be expected. Thus, the authors' claim that the propagation velocity of the pulsed carrier was that of the phase velocity in the waveguide cannot be confirmed from their data.

The authors did conduct measurements of the phase velocity in the test waveguide using standard means (standing wave detector and wavemeter) and found results consistent with theory, suggesting normal operation of the waveguide. However, measurement of the propagation delay in a waveguide which was significantly longer could have provided a more accurate velocity estimate, and when compared with the delays in the 1.66-m long waveguide, could have been used to determine the systematic offsets due to detector response delays.

B. Transmission Through Air

The second experiment was conducted by propagating a pulse modulated carrier at 8.245 GHz beween two small-aperture antennas. An open ended waveguide (presumably including the transmitted pulse detector) was used for transmission, and a small-horn antenna was coupled to the receiving detector. When the two antennas were placed directly facing each other, separated by 42.7 cm, the transit time measured was 2.66 ns. The authors ascribe 1.246 ns of this delay to the propagation time within the transmitting and receiving waveguides. (They do not indicate as to whether phase or group velocity was used in the calculation.) The result was an inferred propagation velocity of 3.02 x 10^8 m/s. As the receiving horn was then moved in a lateral direction along the *H*-plane, the apparent delay remained constant, even though the distance increased significantly. The authors interpreted this to mean that the pulse propagtion velocity was equal to the phase velocity, or $c/\cos\theta$, where θ was the angle from the transmitting aperture boresight on the *H*-plane. However, the magnitude of the electric field radiated by the open TE_{10} waveguide aperture on the *H*-plane (WR-90 waveguide operating at 8.245 GHz) varies as $\left[\cos(2\sin\theta)/1 - 1.6\,\sin^2\theta\right]$ (see, e.g., [5].) Therefore, the parasitic capacitance in the receiving detector, which is proportional to the incident field intensity, would also vary as this factor. This then would lead to a positionally dependent delay term in the receiving detector that would be roughly proportional to $\cos\theta$. As a result, it is very likely that the authors measured a positionally dependent detector response delay rather than a positionally dependent propagation velocity.

Such an effect could have been detected if the experiment were repeated using several different initial spacings between the two aperture antennas, since the positionally dependent delays would be reduced at much greater spacings. Likewise, any systematic offsets due to the different response times of the detectors could have been detected and quantified.

III. CONCLUSION

Careful analysis of the experimental approaches and the inferred results from the work described in Giakos and Ishii [1] and in Ishii and Giakos [2], suggest that significant sources of systematic error were not considered by the authors. As a result, we conclude that no reliable evidence has been presented demonstrating pulse propagation at velocities exceeding *c*. However, additional measurement steps could be added to those described by the authors to correct for such systematic errors and significantly improve the accuracy of such measurements.

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Response to P. G. Steffes' and G. P. Rodrigue's "Comments on 'Rapid Pulsed Microwave Propagation'"

George C. Giakos and T. Koryu Ishii, *Senior Member, IEEE*

Abstract—**The authors defend their experimental observation against comments made by P. G. Steffes and G. P. Rodrigue on "Rapid Pulsed Microwave Propagation." The comment-writers' misconception on the authors' experimental systems and pulse modulated microwave detection is cleared. The authors show that the accuracy of propagation measurements presented in this study is better than 0.2%.**

It came to the authors' attention that the authors' early works [1]–[2] are commented by Steffes and Rodrigue [3]. The authors offer the following responses.

The comments-writers state, "the output of the pulse generator was also fed to an HP 1415 time-domain reflectometer (TDR), as a sweep trigger." The fact is that the TDR is providing to the pulse generator the synchronous signals.

The comment-writers state, "typically such detectors have rise times on the order of 1–200 ns . . . " If the comments-writers were correct, the cutoff frequency of this detector diode would be 1 GHz for 1 ns and 5 MHz for 200 ns. The fact is that the detector diodes used in the authors observation are 1N23C for the transmitter probe and 1N23WG for the receiver. These are X-band mixer diodes [7]. Since WWII, 1N23's have been properly and successfully used for X-band microwave detection. Usage of the magnifier at 1 ns/cm sensitivity, for the published measurement of 5.0245 x 10^8 m/s [1] is shown in Table I. As seen from Table I and Table II as well, the authors' system accuracy is better than "+5 ns." Therefore, the comment-writers' statement, "the reported 22 ns pulse rise time . . . accuracies of no better than +5 ns could be expected . . . cannot be confirmed from their data," is not applicable to the authors' work [1]–[2]. Description of the detectors used in this experimental set-up is offered in [8]. On the transmitting side, an HP-X880 E–H tuner was inserted in front of an FXR-B200A RF tunable probe. Transmitted microwave signal was detected through an 1 N23C Microwave point contact mixer diode placed inside the probe. The receiver detector used was an 1N23WG Microwave point contact diode placed inside a 34X1 SPERRY Microline detector-mixer mount terminated by an adjustable shorting section that serves as an impedance matching device. These diodes were operated in their "square law" region. An E–H tuner formed by using two HP-X920 adjustable shorts was inserted in front of the receiving detector.

The comment-writers state, "Therefore, the parasitic capacitance in the receiving detector, which is proportional to the incident field intensity would also vary as this factor." This statement is contrary to commonly accepted semiconductor junction theory [5].

The comment-writers state, "this then would lead to a positionally dependent delay term in the receiver detector which also would be roughly proportional to $\cos\theta$." If the comment-writers' are correct, then the signal-to-noise ratio of the detector decreases as $\cos\theta$. Therefore, the time delay should increase instead of remaining constant [6], [8]. Thus, the comment-writers' statement does not apply to the authors' work.

The comment-writers state, "such an effect could have been detected if . . . " This has been done in [8]. Some results are shown in Table II. As seen from Table II, "such an effect" was not detected. On the other hand, the time scale of the time-domain reflectometer (TDR) was calibrated using TEM mode open space propagation. Thus, the technical critique offered by the comment-writers does not apply to the authors' work.

The comment-writer concluded, "careful analysis of the experimental approaches . . . significant sources of systematic errors . . . " The calibration methods employed are the differential time delay method and the composite propagation method [8]. In the first method, the time delay among the receiving pulse-modulated microwaves at different incremental open air distances of the receiver antenna with

TABLE I
USAGE OF THE TDR MAGNIFIER FOR THE MEASUREMENT OF 5.0245 × 10^8 M/S

Trial #	Transmitter Magnifier Reading	Receiver Magnifier Reading
1	8.815	8.880
2	8.815	8.882
3	8.816	8.881
4	8.815	8.881
5	8.815	8.881
6	8.816	8.881
7	8.815	8.881
8	8.815	8.881
9	8.815	8.881
10	8.815	8.881
11	8.815	8.881
12	8.816	8.881
13	8.815	8.880
14	8.815	8.881
15	8.817	8.881
16	8.815	8.881
17	8.817	8.881
18	8.815	8.882
19	8.815	8.881
20	8.815	8.881
21	8.815	8.881
22	8.816	8.881
23	8.815	8.881
24	8.815	8.882
25	8.816	8.881
26	8.815	8.881
27	8.815	8.881
28	8.816	8.881
29	8.815	8.881
30	8.815	8.881

Average transmitter magnifier reading: 8.815.
Average receiver magnifier reading: 8.881.
Transit time: 50 ns × (8.881 − 8.815) = 3.3 ns.

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TABLE II
SPEED MASUREMENTS AT DIFFERENT OPEN AIR PROPAGATION DISTANCES

Test* Distance (cm)	Propagation Time (ns)	Propagation Speed (10^8 m/s)
13.5	.0447	3.020
42.8	1.414	3.019
71.5	2.379	3.005
153.0	5.100	3.000
231.0	7.675	3.009
247.0	8.253	2.992
350.0	11.670	2.999
394.0	13.100	3.007
700.0	23.300	3.010

Measured average velocity 3.006 × 10^8 m/s.
Transmitter and receiver antennas are facing directly to each other.

respect to the stationary transmitter, facing directly to each other, were measured. The velocity of propagation of the pulse-modulated microwaves propagating in open air was found to be approximately equal to the intrinsic velocity of light c. In the composite propagation method, the transit time taken by the pulse-modulated microwaves to travel from the transmitting to the receiving detectors was measured on the TDR display. Then, the theoretical transit time corresponding to guided TE_{10} pulse-modulated microwaves travelling with the phase velocity was subtracted from it and a transit time associated to open air TEM waves propagating with the intrinsic velocity c, resulted. Both methods produced similar calibration results. Some of these results are shown in Table II. Furthermore, each time that the averaged open-air transit time—measured through the differential time delay method—was subtracted from the displayed on the TDR composite transit time, transit times associated to TE_{10} guided modes propagating with the phase velocity, resulted. The whole calibration procedure ruled out the possibility of any source of error. Similarly, for the waveguide propagation experiments, differential time delay measurements among the receiving signals at different klystron operating frequencies accompanied with transit time measurements between the transmitting and the receiving microwave signals produced similar time-domain results. Measured transit times and velocities of propagation of pulse-modulated guided microwaves are reported in [8] and shown in Fig. 1, Tables I and III. Black circles in Fig. 1 correspond to measured velocities of the microwave signals. Thus, the conclusive statements offered by the comment-writers are not applicable to the authors' work [1]–[2].

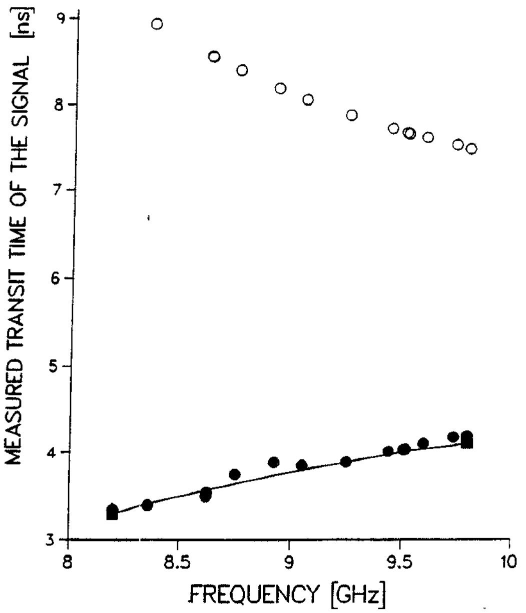

Fig. 1. Measured transit time curve of the signal in comparison with the transit times estimated based on theoretical values of phase and group velocity, for various klystron operating frequencies. Black circles indicate measured values while the continuous line and white circles indicate theoretical transit times based on phase and group velocities respectively. The measured transit time of the signal listed in this table is the average of 30 trials.

The rest of the points raised by the comment-writers are arbitrary in nature. Therefore, there is no scientific merit for their discussion.

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TABLE III
ACCURACY OF MEASURED VELOCITY OF THE SIGNAL COMPARED TO THE THEORETICAL PHASE VELOCITY IN AN X-BAND RECTANGULAR WAVEGUIDE. THE MEASURED VELOCITY OF THE SIGNAL LISTED IN THIS TABLE IS THE AVERAGE OF 30 TRIALS

Klystron Frequency (GHz)	Theoretical Phase Velocity (× 10^8 m/s)	Theoretical Group Velocity (× 10^8 m/s)	Measured Velocity of the Signal (× 10^8 m/s)	% Error
8.202	5.0245	1.791	5.0245	0.0
8.36	4.85	1.855	4.877	0.56
8.622	4.642	1.938	4.737	2.04
8.625	4.635	1.9417	4.670	0.75
8.75	4.550	1.978	4.421	2.835
8.925	4.437	2.028	4.270	3.76
9.05	4.364	2.0623	4.306	1.329
9.25	4.267	2.1092	4.267	0.0
9.44	4.18	2.153	4.14	0.956
9.508	4.149	2.1691	4.121	0.674
9.518	4.143	2.172	4.119	0.579
9.6	4.12	2.184	4.05	1.699
9.738	4.075	2.208	3.98	2.331
9.78	4.040	2.227	3.967	1.806

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Comments on "Rapid Pulsed Microwave Propagation"

Roger B. Marks, *Senior Member, IEEE*

Abstract—**This letter discusses a recently published letter that reports experimental evidence of electromagnetic pulses propagating faster than the speed of light. It argues that such results contradict Maxwell's equations. Limitations of the experiment are examined.**

I. INTRODUCTION

A recent letter [1], along with several related publications [2]–[4], reports experimental evidence of electromagnetic pulses that propagate faster than the free-space speed of light $c = 1/\sqrt{\varepsilon_o \mu_o}$. These papers suggest that the phase velocity, which is well known to exceed c in some circumstances, may equal the signal velocity. In fact, both the analytical and experimental results contradict Maxwell's equations, which directly imply that electromagnetic fields propagate with speed c.

The maximum velocity of signal propagation can be determined directly from Maxwell's equations in time-dependent form, since the scalar potential and the three Cartesian components of the vector potential each satisfy the inhomogeneous wave equation:

$$\nabla^2 \phi(\boldsymbol{r},t) - \frac{1}{c^2}\frac{\partial^2 \phi(\boldsymbol{r},t)}{\partial t^2} = -4\pi f(\boldsymbol{r},t) \qquad (1)$$

where $f(\boldsymbol{r},t)$ represents the sources. Equation (1) has the explicit solution [5]

$$\phi(\boldsymbol{r},t) = \int \frac{f(\boldsymbol{r}', t - |\boldsymbol{r}-\boldsymbol{r}'|/c)}{|\boldsymbol{r}-\boldsymbol{r}'|} d^3\boldsymbol{r}'. \qquad (2)$$

Fields generated at $\boldsymbol{r}'$ therefore arrive at $\boldsymbol{r}$ after a delay of $|\boldsymbol{r}-\boldsymbol{r}'|/c$. In other words, the fields radiated by the source propagate with speed c. Due to interference among multiple sources, the *total* field may vanish at time $|\boldsymbol{r}-\boldsymbol{r}'|/c$ even though a source exists at $\boldsymbol{r}'$ when $t = 0$. As a result, the net signal may effectively propagate slower than c, but under no circumstances can it propagate faster. In addition to Maxwell's equations, the only assumption required in deriving (2) is the rejection of the noncausal "advanced" potentials that would arrive before being generated.

The experimental results of [1]–[4] are unconvincing. One major problem is measurement precision. For instance, all of the results of the free-space propagation experiment are insignificant if the accuracy of the delay measurement is worse than 0.24 ns, which implies that the transmitted and received signals need to be located with 0.12 ns resolution. However, the pulse has a stated rise time of 22 ns at the *source* and could be expected to be much less sharp at the receiver. Locating the "leading edge" of such a pulse to within 0.12 ns is a Herculean task. Even the reported instrument resolution ("less than" 0.15 ns [4]), which presumably applies to a square wave and therefore, provides a lower bound to the overall resolution, is inadequate. The authors conclude that the system accuracy is 0.1% because their measured value of c, based on several estimated correction factors, is within 0.1% of the accepted value. This reasoning seems to lead to an overly optimistic conclusion.

While both the analyses and the measurements presented in [1]–[4] are naive, they agree to an astonishing degree. Unfortunately, the experimental results are not persuasive. A far more critical view of the experiment is essential before the scientific community will readily accept the legitimacy of what would be one of the most startling observations of the century.

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Response to R. B. Marks' "Comments on 'Rapid Microwave Propagation'"

George C. Giakos and T. Koryu Ishii, *Senior Member, IEEE*

Abstract—**Recently published experimental results in "Rapid Pulsed Microwave Propagation," which is commented by R. B. Marks, do not contradict Maxwell's equations. The experimental "limitations" are defended.**

It came to the authors' attention that the authors' recent work, "Rapid Pulsed Microwave Propagation" is commented on by Marks [1]. The authors present the following responses to his comments.

The comment-writer states, " . . . electromagnetic pulses propagation . . . " It should be " . . . pulsed microwaves propagating . . . "

The comment-writer states, "these papers suggest that the phase velocity . . . may equal the signal velocity." That is not stated in the

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author's work [2]. Instead a new term the velocity of the signal [10] which is unrelated to the signal velocity concept [12] is used. This velocity of the signal is equal to c in free space for TEM mode propagation and it is greater for non-TEM mode propagation [3], [5], [6], [8], and [10].

The comment-writer states, " . . . electromagnetic fields propagate with c." Correct statement should be " . . . the change or variation of electromagnetic fields propagates with c." It can be shown, starting from Maxwell's equations, that the speed of propagation of the change of electromagnetic fields is c if the mode of propagation is TEM mode as observed in the direction of propagation of interest. Starting from the same Maxwell's equations, the speed of propagation of the change of electromagnetic fields is greater than c if the mode of the propagation is non-TEM mode [3], [5], [6], [8], [9], and [10].

The comment-writer states, "In fact, both the analytical and experimental results contradict Maxwell's equations." The author's analysis [3] [10] and experimental observation [2] show that it does not contradict Maxwell's equations.

Non-TEM waves propagating with velocities of propagation equal to the apparent phase velocity in a specific direction of interest that is larger than 3 are also products of solution of Maxwell's equations [3], [5], [6], [8], and [10].

The comment-writer states, "The maximum velocity . . . can be determined directly from Maxwell's equations . . . " The comment-writer's "Eq. (1)" is not a Maxwell's equation. It is Helmholtz wave equation ([4, p. 428]) [5], [6].

The comment-writer uses the inhomogeneous wave equation "Eq. (1)" and "the explicit solution" "Eq. (2)." Both of these "Eq. (1)" and "Eq. (2)" include sources. Therefore, these do not apply to the author's cases. The authors' cases are microwave propagation in an empty waveguide or in an open space that does not include the source. For the propagation in an empty waveguide and in empty open space, as seen in [4, p. 340, (7.2) and (8.19)] and other authors [5] [6], homogeneous Helmholtz wave equation and its solutions should be applied. The comment-writer should note that the integral of his "Eq. (2)" is over the sources. The authors' analysis and observation are made in the source free region of the media. Therefore, application of the comment-writer "Eq. (1)" and "Eq. (2)" in this study is inappropriate.

Contrary to the comment-writer's statement, his "Eq. (2)" is not "the explicit solution." No information of propagation modes is explicitly shown in his "Eq. (2)." For that matter, his "Eq. (1)" does not have any information of the propagation modes. Since a differential equation itself cannot determine the propagation mode unless the boundary conditions are given, the comment-writer's "Eq. (1)" and "Eq. (2)" are incapable of determining the propagation modes. Since both "Eq. (1)" and "Eq. (2)" are insufficient to determine the propagation modes, these are insufficient to determine the propagation speed. Therefore, contrary to the comment-writer's statement, "the maximum velocity of signal propagation can "not" be determined directly from Maxwell's equations."

The comment-writer's "Eq. (2)" is meaningful only if the electromagnetic waves propagate from $\boldsymbol{r}'$ to $\boldsymbol{r}$ in the TEM mode with speed c. If the mode of propagation is non-TEM mode, his "Eq. (2)" is meaningless. In fact his "Eq. (2)" is written under an assumption that the electromagnetic waves propagate from $\boldsymbol{r}'$ to $\boldsymbol{r}$ with speed c (p. 226 Jackson [4]). No non-TEM mode propagation is considered. Therefore, neither "Eq. (1)" nor "Eq. (2)" does not determine that "the maximum velocity of signal propagation" is c.

The comment-writer states, "Due to interference among multiple sources, the total field may vanish at time $|\boldsymbol{r} - \boldsymbol{r}'|/c$." If so, there should be a standing wave and the vswr $\rightarrow \infty$. The authors' case are travelling waves. Therefore, the comment-writer's argument does not apply to the authors' cases.

TABLE I

Calibration of Measuring System

Test Distance (m)	Measured Transit Time (ns)	Measured Velocity ($\times 10^8$ m/s)
0.5	1.7	2.98
1.0	3.32	3.01
1.5	4.98	3.01
2.0	6.62	3.02
2.5	8.33	3.00
3.0	10.00	3.00

Measured average velocity 3.003×10^8 m/s.
% error from 3×10^8 m/s = 0.1%.

The comment-writer states, "the net signal may effectively propagate slower than c." But that is not the issue in the authors' work. The issue is the propagation speed of the leading edge of the pulse modulated microwaves, and not the "net signal." In digital communication technique, the signal is regenerated at the receiver end. Therefore, the recognition of the leading edge of the signal is significantly meaningful. The comment-writer's "net signal" is meaningful only for analog communications. The authors' work does not include analog communications. Thus, contrary to the comment-writer's statement, his "Eq. (2)" does not show that "the net signal may effectively propagate slower than c, but under no circumstances can it propagate faster."

The comment-writer states, "if the accuracy of the delay measurement is worse than 0.24 ns." The actual accuracy of the experimental set-up in the authors' work [2] is 0.01 ns at 1 ns/cm sensitivity with the use of the magnifier [11]. The comment-writer states, "locating the 'leading edge' of such a pulse within 0.12 ns is a Herculean task." Actually, the task is "a piece of cake." As seen from Fig. 2 of the authors' work [2] after 0.12 ns later from the observed leading edge, the observed pulse rises to 1.5 times (3.52 dB) of the displaying TDR oscilloscope noise. Therefore it is easy to observe the "leading edge."

The reported instrument resolution "less than 0.15 ns [7]" should be correctly interpreted as "better than 0.15 ns." The most probable value of the authors' instrument resolution in the authors' work [2] is found to be 0.01 ns with the use of the magnifier [11]. The authors' experimental system was calibrated using TEM mode open space propagation [10] for the propagation velocity measurements. The calibration methods used are the differential time delay methods [10] and the composite propagation method [10]. Both methods produced similar calibration results. The calibration results are shown in Table I. Therefore, the authors' measuring system accuracy of 0.1% on propagation speed measurement should not be taken lightly.

The rest of the comment-writer's comments are arbitrary and there is no scientific value for further discussion.

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Correction to "Diagonalization of Difference Operators and System Matrices in the Method of Lines"

R. Pregla, *Senior Member, IEEE*, and W. Pascher

In the above letter,[1] the following corrections are necessary.

In (22), the right pair of brackets must contain a vector:

$$\begin{bmatrix} \bar{\bar{\boldsymbol{E}}}_B \\ \bar{\bar{\boldsymbol{H}}}_B \end{bmatrix} = \begin{bmatrix} \bar{\bar{\boldsymbol{V}}} & \bar{\bar{\boldsymbol{Z}}} \\ \bar{\bar{\boldsymbol{Y}}} & \bar{\bar{\boldsymbol{V}}} \end{bmatrix} \begin{bmatrix} \bar{\bar{\boldsymbol{E}}}_A \\ \bar{\bar{\boldsymbol{H}}}_A \end{bmatrix}. \tag{22}$$

In (31), $\hat{\boldsymbol{\lambda}}_e$ and $\hat{\boldsymbol{\lambda}}_h$ must be replaced by $\hat{\boldsymbol{I}}_e$ and $\hat{\boldsymbol{I}}_h$, respectively:

$$\bar{\boldsymbol{y}} = \begin{bmatrix} \hat{\bar{\boldsymbol{\lambda}}}^2_{zh} - \varepsilon_r \hat{\boldsymbol{I}}_h & -\hat{\bar{\boldsymbol{\delta}}}_x \hat{\bar{\boldsymbol{\delta}}}_z \\ -\hat{\bar{\boldsymbol{\delta}}}^{*t}_z \hat{\bar{\boldsymbol{\delta}}}^{*t}_x & \hat{\bar{\boldsymbol{\lambda}}}^2_{xe} - \varepsilon_r \hat{\boldsymbol{I}}_e \end{bmatrix}. \tag{31}$$

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