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To cite this version:
Short Communication

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(Received 4 February 1993, accepted 9 February 1993)

Abstract. — Recent frequency domain experiments and a corresponding Fourier analysis have shown that the transport of evanescent mode packets in an undersized waveguide may be superluminal. Here we report on high-resolution, direct time domain measurements which confirm these results.

Evanescent modes are solutions of the Helmholtz wave equation which have a purely imaginary eigenvalue for the electromagnetic wave vector $k$. They have no spacial phase variation, consequently their phase shift is zero during propagation. Recently we have shown that the measured dispersion relation of evanescent modes in rectangular waveguides follow this mathematical description within a high degree of accuracy [1, 2]. According to Fourier analysis this stationary, frequency dependent behavior may be translated into the time domain to determine transfer times. This was carried out with experimental frequency-domain data [2]. Also the analogies to the tunneling time problem of quantum mechanics was outlined which suggests to use the term "tunneling" for both cases [3, 4]. The resulting transfer times in terms of the time delay of the center of gravity or the maximum value of the wave packet yielded superluminal values, i.e. times which are short compared with the ratio $L/c$ ($L$ being the evanescent waveguide length and $c$ the velocity of light in vacuum). Recent single-photon tunneling experiments also point to superluminal barrier traversal [5]. Under certain conditions ("opaque barrier") even zero-times can be achieved, i.e. an instantaneous "traversal" of electromagnetic packets through space seems possible [2, 3]. To confirm the results of the frequency domain measurements and the corresponding Fourier transform, we have now performed direct time domain measurements.

1. Experimental procedure.

A radio-frequency source (HP8341B synthesizer) was used which modulates the amplitude of its carrier frequency in form of pulses (on/off ratio larger than 80 dB, i.e. eight orders of magnitude in power). A transition analyzer (HP71500, "TA") detects corresponding pulse envelopes in two separate receiver channels and simultaneously controls the source with respect to pulse and carrier characteristics (operating mode: $+5$ dBm source power, 1 $\mu$s pulse width and 10 kHz pulse repetition frequency, 62.5 kHz digital noise filter equivalent bandwidth of the receivers). Both receivers trigger synchronously with respect to a time point which is defined by one of them, the accuracy of the time sampling points is in the range of 10 psec under the present conditions [6]. The pulses from the source were splitted by a coaxial power splitter.
(HP11667A) into two paths. One path was connected to one channel of the TA (transition analyzer) and was left unchanged during all measurements to get a stable time reference point for triggering. This can be achieved by choosing a very early time point on the pulse envelope being detected in this channel. Consequently the trigger reference point does not depend on the other, measuring path behind the power splitter, since reflections coming from there occur at later times only.

In the measuring path two coaxial/X-band waveguide adaptors were inserted with sufficient coaxial line length (> 1 m) between both the power splitter output on one side and the second channel input of the TA on the other side. Thus multiple reflections which are induced by impedance changes in the set-up, especially that at the waveguide flanges to the cut-off waveguide sections, occur rather late on the pulse envelope. This allows the comparison of the rising edges of the pulses on a large time scale without distortion.

Additionally a coaxial step attenuator (HP8495B with 10 dB steps) was inserted in the measuring path with which the level of the pulse at the input of the TA can be equalized. This corresponds to a normalization process of the pulse amplitude. Doing this directly in the hardware of the set-up has the advantage that dependencies of the TA receiver noise floor on the absolute signal levels can be eliminated and the measured pulse envelopes can be directly compared. On the other hand the step attenuator must have a flat frequency response for this purpose, especially its electrical phase length must be independent of the chosen attenuation. This was checked, and the variations in delay time were proven to be smaller than 25 ps and changes of the pulse envelope couldn't be resolved at all.

2. Results and discussion.

The following measurements were carried out:

a) A thru-connection of both X-band waveguide adaptors served as the time reference (length of evanescent waveguide is zero) while the attenuation in this path by the step attenuator was chosen to be 40 dB (power attenuation by a factor $10^4$). The corresponding rising edge of the pulses is always displayed as a solid line in figures 1 and 2.

b) A Ku-band waveguide of 60 mm length was inserted between the two X-band waveguide adaptors (cross-section of X-band is $10.16 \times 22.86 \text{ mm}^2$ and that of Ku-band $7.90 \times 15.80 \text{ mm}^2$), the cut-off frequencies are 9.49 GHz for the larger and 6.56 GHz for the smaller waveguide which corresponds to the experimental conditions of reference [2]. Thus an evanescent region is created by the Ku-band waveguide in the measuring path if the carrier frequency is between these two cut-off frequencies. The step attenuator was adjusted to a value of 0 dB (no attenuation).

Now we have chosen the carrier frequency such that the attenuation in the evanescent Ku-band waveguide region under the conditions of b) equaled 40 dB as in a). The ideal and well-defined position for this normalization adjustment would be at the maximum values of the undistorted pulse envelopes. However, the coaxial cables in the set-up were not long enough to reach this time point without envelope disturbances by the superposition of multiple reflections. Therefore an earlier point had to be chosen. This choice is somewhat arbitrary and therefore simply two different carrier frequencies were both measured which gave two extremal situations: a lower carrier frequency of 8.644 GHz yielded rising edges of the pulses where the amplitude behind the evanescent waveguide region was always smaller than that of the reference pulse (see Fig. 1). With the higher carrier frequency of 8.658 GHz it was the other way round (Fig. 2), already inducing an artificial non-causality to the reference after 2.5 nsec of pulse duration.
Fig. 1. — Power envelope of 8.644 GHz frequency $f_{\text{car}}$ for the rising edge of the reference pulse (zero length of evanescent waveguide section, 40 dB attenuation of step attenuator, solid line) and the pulse behind the evanescent waveguide region (length of 60 mm, 0 dB attenuation of step attenuator, dashed line). 800 equidistant time points were taken for each trace.

Fig. 2. — Power envelope of 8.658 GHz carrier frequency $f_{\text{car}}$ for the rising edge of the reference pulse (zero length of evanescent waveguide section, 40 dB attenuation of step attenuator, solid line) and the pulse behind the evanescent waveguide region (length of 60 mm, 0 dB attenuation of step attenuator, dashed line). 1000 equidistant time points were taken for each trace.

In figures 1 and 2 the two situations are displayed both on a linear and a logarithmic power scale. On the logarithmic scale, there is a systematic small kink in the low power range with a corresponding deviation between the two pulse envelopes. It was identified as an artefact being induced by the pulsed source: in this low power range at the start of the switch-on process, some small spikes are superposed on the envelope. If the step attenuator is at 40
dB all frequency components and therefore all time structures are equally attenuated so that these structures remain small and are not visible. However, the evanescent waveguide region acts as a very effective high-pass filter and does not attenuate frequency components above the cut-off frequency. Therefore these structures become visible and cause an alleged non-causality since they are over-amplified by the normalization process compared to the reference. But this effect influences only the lowest part of the envelopes and is not important for the comparison on the linear scale to determine the maximum value and/or the center of gravity. At this point it should also be mentioned that the used digital noise filter of the TA just gives the power of the carrier frequency component at the respective sampling time point; other frequency components are not measured (compression of the amplitude modulation sidebands to zero [6]). Consequently Sommerfeld or Brillouin precursors would not be displayed even if they would have a significant amplitude under the present conditions [7]. On the other hand such contributions could be made very small by an adequate (Gaussian) shaping of the pulse envelope so that the interpretation given below is not affected as long as only the center of gravity or the maximum value of the pulse is of interest. On the other hand, this issue is important with respect to the signal or front velocity. If evanescent modes carry superluminal signals they must be detected even in front of these luminal precursors.

From the data presented in figures 1 and 2 the following conclusions can be drawn:

The deformation of the pulse envelope behind the evanescent waveguide region is very small and can hardly be resolved which is consistent with the frequency domain results [1-3]. Two extremal situations concerning the amplitude normalization were chosen. The time delay of the pulse behind the evanescent waveguide region must be smaller than the difference being visible in figure 1 which gives the upper limit. On the other hand, the 60 mm length of this region corresponds to a delay time of 0.2 nsec of light in vacuum, this is clearly longer than the measured delay in the first 5 nsec duration of the pulse - superluminal conditions are present both for the center of gravity and the maximum value of the electromagnetic packet. Furthermore this confirms the correctness of the frequency domain data and the corresponding Fourier evaluation [2, 3]. The zero-time traversal described in references [2] and [3] proves to be correct, i.e. there is no additional time delay caused by an additional length of the evanescent region.

Acknowledgements.

We are very grateful for essential technical support by Hewlett-Packard/Bad Homburg (H. Aichmann and W. Strasser).

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