Negative Group Velocity and Spin-Flip in Microwave Adaptors

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Abstract A Fabry-Perot like interferometer with two microwaveguide adaptors as reflectors creates a passive dielectric medium with a negative group delay time due to polarization shift. A rotational strain of the polarization vector by one of the adaptors is coupled with a drastic negative group velocity. The adapted rectangular and circular waveguides have the same dispersion. The input rectangular waveguide mode is linearly polarized, whereas the basic mode of the adapted circular waveguide is circularly polarized. A 667 wavelengths long circular waveguide connects the input with the output adaptor. Experiments are performed in the frequency and in the time domain. We describe, how the helical polarization change and the spin-flip of the two different circular wave modes produce the observed negative group velocity.

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I. INTRODUCTION

Previously the observation of backward pulse propagation through a medium with negative group velocity was published by Gehring et al. [1]. The experiment was carried out in the infrared and the active medium was designed with the help of an Erbium doped optical fiber amplifier. Backward waves of guided microwaves have been studied by Pincherle [2] in 1944, by Clarricoats [3] in 1963, and different other authors. Resonant absorbing and amplifying media have been studied in order to demonstrate negative group velocities of electromagnetic waves by Segard and Macke [4] and by Wang et al. [5]. In the previous studies negative group velocity has been observed in frequency regions near absorption or gain features. A review article on controlling light by active media are presented in Ref. [6]. Velocity studies on faster than light tunneling are reviewed in Ref. [7] recently.

FIG. 1: Adapters from rectangular (frequency X-band 8.2 GHz - 12.4 GHz; wavelength 36.6 mm - 24.2 mm) to circular waveguide and vice versa. The rectangular and circular guides have the same cut-off frequency of 6.5 GHz and the same dispersion relation. The inside guide dimensions are 10.16 mm · 22.86 mm and 27 mm diameter, respectively. The total adaptor length is 105 mm.

Incidentally, a sophisticated mechanical experiment carried out by Beth provided quantitative evidence of angular photon momentum, i.e. of the spin in 1936 [8]. The photon spin is related to the electric helical polarization of a photon. This connection was applied to invert the spins of all the photons in a circularly polarized light beam by $2\hbar$ from $-1\hbar$ to $+1\hbar$. Here we report on a microwave experiment with the passive waveguide mode adaptors, which can cause an extreme negative group velocity and a spin-flip. Two adaptors, which are separated by a circular metal pipe act similarly to a Fabry-Perot interferometer (F-P) with a negative group delay time at periodical frequency intervals. However, this phenomenon happens only if the input polarization of the first and the output polarization of the second adaptor are not parallel. The microwaveguide adaptors are displayed in Fig. 1, the angle between the orientation of the rectangular input and output parts is defined as α. Only for angles $\alpha > 0^0$ and $< 180^0$ the F-P like behavior and the negative group velocity are observed. In the experiment, the connecting circular waveguide was turned up between 0^0 and 90^0. Polarization is conserved over a distance of 20 m in the experimental set-up. In the case of the TV satellite communication, polarization is conserved over a distance of 35,786 km.

A F-P interferometer can be described as a one-dimensional cavity constructed by two tunneling barriers. In such Fabry-Perot set-ups, superluminal velocities have been observed with microwave [9, 10] and infrared digital signals [11]. Negative group velocities in special Fabry-Perot structures have been investigated in Refs.[15, 16], for instance. In the investigated set-up Fig. 2 periodical interferometer structures of the complex transmission and reflection begin above 0^o of the angle α and increases up to 90^o.

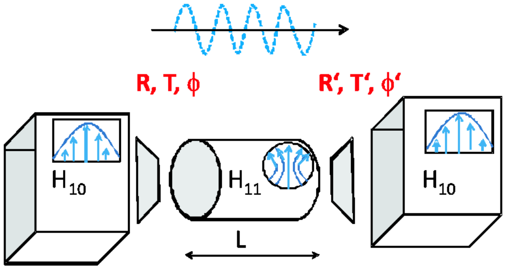

FIG. 2: Experimental set-up. From left: Signal input via rectangular wave guide with H_{10} mode adapter to circular wave guide with H_{11} mode (R, T, Φ). The second adaptor transmits the circular mode back to a rectangular wave guide with H_{10} mode (R', T', Φ'). R, R', Φ, Φ' L are reflections, phase shifts at the adaptors, and L the length of the circular waveguide between the adaptors. The field distribution in the waveguide cross section is sketched.

The frequency band width between two resonance transitions of a F-P interferometer is given by the relation

$$\Delta\nu = \frac{c}{n2L}, \tag{1}$$

where c is the velocity of light in vacuum, n is the refractive index of the material between the two reflectors, and L the distance of the reflectors. This relation is fulfilled in the studied experimental design with mode adaptors as mirrors. For instance, with L = 20 m and n ≈ 1.5 we obtain a value of ≈ 5 MHz.

As we shall see below, only the frequency band width between the transmission maxima of the adaptor design agrees with a F-P interferometer but not the shape of the transmission spectra or disappearing periodical structures as α goes to zero. The resonance dips are maximal, when the input and output rectangular wave guides are oriented perpendicularly. The transmission of the set-up is maximal, whereas the periodic structures disappear at an angle $\alpha = 0$. Parallel orientation of the input and output rectangular waveguides represents the normal technical use of such a set-up.

II. EXPERIMENTAL RESULTS

The rectangular X-band waveguide and the circular guide have the same frequency dependent dispersion and the same cut-off frequency of 6.5 GHz. The set-up is sketched in Fig. 2. The input in the rectangular waveguide with the H_{10} mode excites circular H_{11} modes in the first adapter. The electric field distribution of the two modes are sketched in Fig.2. The circular modes (right and left circularly polarized) are transmitted on a circular wave guide of length L and transduced at the second adapter back to the H_{10} mode in the rectangular waveguide. Depending on the angle between the rectangular input and output waveguide we obtain weak or strong F-P resonances.

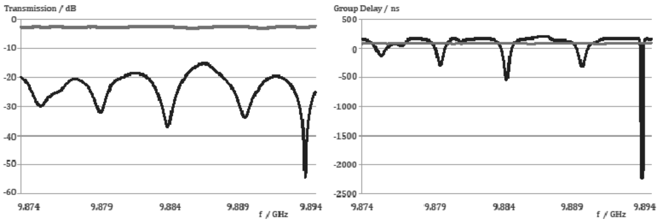

FIG. 3: Transmission vs frequency of the 20 m circular waveguide. The adapters are oriented $\alpha = 0$ (attenuation of ≈ -2.5 dB, grey line) and $\alpha = 90^0$ (attenuation oscillations between -15 dB and -55 dB). The figure displays the frequency range between 9.874 GHz and 9.894 GHz. Average periodicity of the structure is ≈ 5 MHz. Right: Group delay time vs frequency of the same set-up. (Remember the vacuum delay of 20 m is 67 ns, whereas the transmission time for $\alpha = 0^0$ is ≈ 100 ns, grey line). The negative delay time of 2.2 μs equals that measured in the time domain also at 9.865 GHz as seen in Fig. 4.

The phase, transmission, and reflection structures are periodical with a frequency band width according to the Eq. 1. We have measured lengths L of 0.2, 5, and 20 m. The transmission shows a drastic deviation from a classical F-P interferometer since the maxima are very broad, whereas the minima are very narrow in frequency.

At resonance frequencies, transmission minima up to -55 dB were measured. The important result at the transmission minima was a negative phase shift and thus a negative group delay time up to -2.2 μs.

The measurements were carried out in the frequency domain with a network analyzer (Rhode-Schwartz ZVK). In the time domain measurements have been done with an oscilloscope (HP-Infinium 2GSa/s/4ch). The time domain results are in agreement with those obtained in the frequency domain, time domain examples are presented in Fig. 4.

The frequency range of the Ku-band is 12.4 GHz - 18 GHz. The cut-off frequency of the circular and the rectangular guides is 9.5 GHz. The inside waveguide dimensions are 15.8 mm · 7.9 mm the corresponding circular waveguide has an inside diameter of 18.5 mm. For comparison we have investigated the same quantities with Ku-band adaptors and L = 0.2 m. The results are in agreement with those observed in the X-band.

III. DISCUSSION

The experimental results, which are displayed in Figs. 3-4 are obtained for an adapter distance L = 20 m, which corresponds to 666 wavelengths. Actually, the right signal in Fig. 4 has the same reshaped structure as the infrared backward wave in the active media observed in Ref. [1]. Depending on the angle between input and output polarization, a negative group delay and thus negative group velocity was observed. Examples with a negative velocity of the order of -0.03 c are presented in Figs. 4. The velocity is calculated according to the phase time relations Eq. 3 and from the time shift $\Delta t \approx 2.2$ μs by Eq. 4, in agreement with the time domain data of Fig. 4.

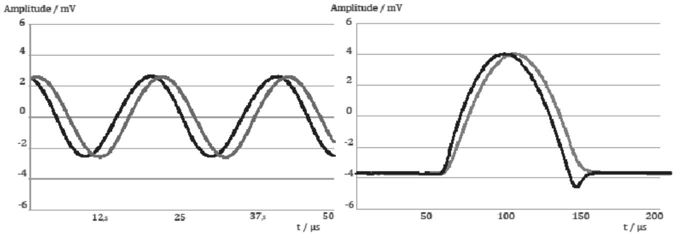

FIG. 4: Left: Delay time of a polarization turned AM 48 kHz wave at a carrier frequency of 9.893 GHz. This fast normalized wave is compared with the grey wave measured at the input of the 20 m long device. The negative shift of ≈ 2 μs points to a negative group velocity of 0.03 c. For instance, the maxima of the fast wave leaves the 20 m waveguide before it has entered it. Remember this happens in a passive medium. Right: Transmission vs time of a signal output at the 20 m circular waveguide (carrier frequency 9.893 GHz). The normalized fast transmitted signal is compared with the grey input signal. The signal output has similar waveform as the infrared one obtained in the active medium displayed in Ref.[1].

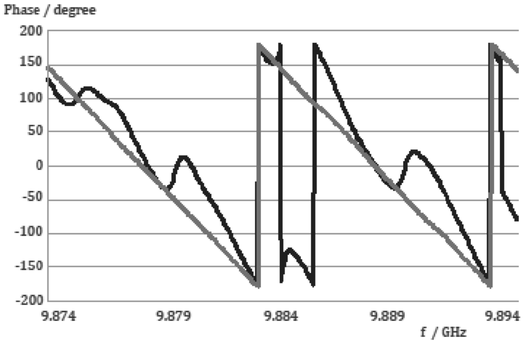

FIG. 5: Phase vs frequency showing the frequency regimes with negative phase. The linear dispersion of the parallel oriented adaptors (grey) corresponds to a group velocity of 0.68 c and a refractive index of 1.5.

The mode and thus the state vector of the photons are given by the first linearly polarized H_{10} mode, which is transduced into right and left circularly polarized H_{11} modes in the first adaptor. If the input and the output polarization of the rectangular waveguides are equal, the linearly polarized H_{10} mode has a small attenuation of -2.5 dB, Fig. 3. The attenuation is essentially due to waveguide losses. With increasing angle α, the transmission decreases since reflection takes place at twisted rectangular output waveguide. For $\alpha = 90^o$ we have a reduced transmission to $\leq$ -15 dB in the X-band set-up with L = 20 m.

There are several theoretical approaches to explain a negative group delay time of special F-P interferometers. For example, the F-P like behavior of waveguide discontinuities by tapered waveguides with the same mode are studied in Ref.[16]. The group delay is given by the relation

$$\begin{aligned} \tau_g &= \frac{d\varphi}{d\omega} && (2)\\ v_g &= L/\tau_g, && (3)\\ v_g &= \frac{L}{\Delta t + L/c}, && (4) \end{aligned}$$

where τ_g and v_g are the group delay time and the group velocity respectively. φ and ω are phase and angular frequency of the wave. Δt is the measured time shift compared with the time spent traversing the same vacuum distance L.

$$\tau_g = \left(\frac{1+R'}{1-R}\right)\frac{L}{v_g} + \left(2\frac{d\phi_t}{d\omega} - \frac{2R'}{1+R'}\frac{d\phi_r'}{d\omega}\right), \quad (5)$$

where R, R', ϕ_t, ϕ_r, L, and ω are reflections, phase shifts at the adaptors, L the length of the circular waveguide between the adaptors, and ω the angular frequency.

In the case that the last component of the delay time equation dominates, the group velocity becomes negative;

$$\left(\frac{2R'}{1+R'}\frac{d\phi_r'}{d\omega}\right) > \left(\frac{1+R'}{1-R}\right)\frac{L}{v_g} + \left(2\frac{d\phi_t}{d\omega}\right) \quad (6)$$

This approach seems not to be appropriate to solve the problem in question, since the quasi mirrors are given by a waveguide discontinuity with the same mode. In our experiment a mode transition is causing the reflection. The latter process is related to the polarization and thus to the spin state of the photons.

Ibanescu et al. studied symmetry breaking axially uniform waveguides [18]. They have calculated anomalous dispersion relations by symmetry breaking. They deduced that anomalous dispersion might take place, if two modes of E (TM) and H (TE) symmetry are close near the long wavelength limit. However, this is not the case for the studied H_{10} and H_{11} modes.

The observation in the pseudo F-P interferometer is described as follows. The H_{10} input mode is linearly polarized and is resolved into two equal amplitude circularly polarized waves H_{11} of opposite hand. In this way the input polarization and spin is conserved. According to the expressions for the two circularly modes H_{11} its angle dependence is

$$E_{rr} = AJ\,\Xi\,exp\,[i(\omega t - kz - \pi/2)] \quad (7)$$

$$E_{rl} = AJ\,\Xi\,exp\,[i(\omega t - kz + \pi/2)] \quad (8)$$

where A,J,Ξ are amplitude and Bessel function terms [19], and E_{rr}, E_{rl} are the radial electric fields right hand and left hand. k, z are the wave number and the propagation direction. Both oppositely polarized circular waves synthesize a linearly polarized wave.

Each of the two circular waves, which differ in phase by $\mp\,\pi/2$ are reflected at the second adaptor by π. Thus the total reflected polarization is turned by $\pi/2$ and travels back to the first adapter and is reflected once more now at the input adaptor forming a long cavity at the proper multiple half wavelength. This takes place at this L of 20 m all 5 MHz. Remarkably, the first adaptor becomes reflective by the second adaptor's reflection. A cavity is formed by the change of the direction of the synthesized linear polarization at the adaptors.

The negative phase vs frequency regime is shown in Fig. 5. At the resonance levels the group delay time becomes superluminal and actually negative up to some μs for a small transmission in a narrow frequency band. The frequency band width varies in the differently shaped resonance dips. This is due to the frequency dependent quality factor of the 20 m long metal pipe resonator.

The reflection and transmission at the mode adaptors experience a negative phase shift at the dispersion around the resonance as displayed in Fig. 5. The resonances are small dips in transmission as in the case of the classical frequency measurement by tunable slightly coupled cavities. This is opposite to the Fabry-Perot interferometer, where the transmission is near to 1. A narrow resonance line has a correspondingly larger negative group delay time and smaller transmission depending on the quality factor in agreement with the measurement.

IV. CONCLUSIONS

Summing up we have observed that mode adaptors in non-parallel orientations exhibit the following properties: The waveguide adaptors act as reflectors if they are not parallel oriented. Transmission decreases and negative group velocities occur with an increasing angle from parallel to perpendicular orientation. The dispersion periodicity of 5 MHz and negative dispersion regions are presented for a 667 wavelength long F-P like set-up in Figs. 3, 5. The negative group delay is observed in the narrow frequency regime of negative dispersion. The most negative delay time occurs at the turning point of the negative part of the dispersion function, Fig. 5. In consequence of the reflection at the metal wall of the twisted waveguide the two helical waves change the handiness and perform a spin-flip see Ref.[8] for instance.

V. ACKNOWLEDGEMENTS

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