Observing ‘back-to-the-future’ phenomenon with photonic chip

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ABSTRACT

The possibility to engineer the group velocity (v_g) of light has attracted much attention in the last couple of years. One of the most exotic phenomena in this research field is the negative v_g phenomenon. Negative v_g implies that if we send light pulse into the optical medium, the peak of the output pulse will leave the output before the peak of the input pulse entering the medium, i.e. a pulse ‘advancement’ or negative delay. This paper will discuss such counter-intuitive ‘back-to-the-future’ phenomenon and its direct time-domain experimental observations on a real photonic chip using measurement equipments available in a typical optical telecommunication laboratory. Comments on the consistency of the phenomenon with the causality principles as well as possible application will also be briefly discussed.

Keywords: negative group velocity, fast-light, slow-light, integrated optics, ring-resonator.

1. Introduction

Group velocity (v_g) defined as v_g = |β/ω|^{-1}, where β and ω are the effective propagation constant and the angular frequency, respectively, is the velocity of the envelope of a superposition of a group of waves with slightly different frequencies. The possibility to engineer the v_g of light has attracted much attention [1-7] in the last couple of years. One of the most exotic phenomena in this research field is the negative v_g phenomenon. Negative v_g implies that if we send light pulse into the optical medium, the peak of the output pulse will leave the output before the peak of the input pulse entering the medium [2, 6], i.e. a pulse ‘advancement’, negative delay, or a ‘back-to-the-future’ phenomenon. It also implies that inside the medium, there is a backward pulse propagation [5]. Although these effects, which in fact have been observed in experiments [2, 5, 6], sound counter-intuitive, their consistency with causality principles has been well verified experimentally [7].

In fact, negative v_g phenomenon is not a new subject, as it has been theoretically studied since a few decades ago [8] and observed experimentally e.g. in photonic crystals, atomic gases, active optical fibers, and left-handed materials. Negative v_g in ring-resonators has also been theoretically studied [3-4]. However, it gained rather little attention due to the absence of applications, as it is understood that there will be no true ‘advancement’ in such a phenomenon as a consequence of the causality principle, hence is not useful for signal processing applications. In our work, we redefine the terms of ‘slow’ and ‘fast’ light, and show that light traveling with negative v_g can also be ‘slow’ (defined as v_g< c) [4], implying its potential for applications like optical sensing, which benefiting from the enhanced light-matter interaction. Hence, the negative v_g phenomenon is not completely useless, but
instead, can be very useful for sensing applications, and therefore its study is indispensable. The study was performed on a single two-port ring-resonator circuit as shown in Fig. 1.

Fig. 1. The two-port ring-resonator circuit under study.

2. The theoretical study

For the theoretical study, we implement the transfer matrix method (TMM) [4] which enables us to reclassify the operation regimes of the ring-resonator circuit into ‘fast’-light with negative $v_g$, ‘slow’-light with negative $v_g$, ‘slow’-light with positive $v_g$, and ‘fast’-light with positive $v_g$. This classification is based on the calculated loss and an intuitive argument that when the light is ‘slow’, it experiences a lot of loss since it stays longer inside the medium. For detail discussions, we refer to Ref. [4].

Using a Fourier transform, the transfer function of optical structure (derived using the TMM), and an inverse Fourier transform, we simulate the pulse temporal behavior as a smooth optical pulse with Gaussian-shaped envelope passing across the ring-resonator circuit operating in the four regimes. The simulation results are shown by Fig. 2. For these simulations we have used particular values of circuit parameters best fitted to our experimental results to be discussed in next section.

Fig. 2. The simulated output pulse shapes for various chip parameter values best fitted to our experimental results. $\kappa$ denotes cross amplitude-coupling-constant between the straight waveguide and the ring-resonator.

3. The direct time-domain experimental observation of pulse passing across optical ring-resonator with negative $v_g$

The theoretical study is supported by experimental verification [6] using a real integrated-optical chip and using measurement equipments available in a typical optical
telecommunication laboratory. For this experiment (see Fig. 3) we used a Si$_3$N$_4$-based integrated-optical chip [9] fabricated by LioniX B.V. [10] which has thermo-optically controllable coupling-constant and ring resonant wavelength. This photonic chip was initially prepared as true-time-delay chip [9] as beam forming circuit for phase array antenna for astronomical applications. By sending an electronically smoothened pulse through the ring-resonator operating in various operation conditions from under coupling, through critical coupling, to over coupling conditions; we observed pulse advancement, pulse splitting, and pulse delay when light at the resonant peak experiences negative $v_g$, transition between positive and negative $v_g$, and positive $v_g$, respectively, as shown in Fig. 4. The delay is measured with respect to a reference condition obtained by putting the ring in an off-resonance condition, a condition which approximately represents a ring-less structure. These pulse temporal behaviors are well verified also using group-delay measurements employing a modulation phase-shift method. The experimental results qualitatively agree with the results of our simulations (see Fig. 2). To the best of our knowledge, our measurement result reported in Ref. [6] is the first direct experimental observation on pulse advancement and pulse splitting in integrated-optical ring-resonator circuit.

**Fig. 3.** Schematic picture of the measurement set-up. EDFA=erbium-doped fiber amplifier, PC=polarization controller, POL=polarizer, PMF=polarization maintaining fiber, TO=thermo-optic modulator

4. The causality of the phenomenon

In these measurement results, the causality relation is not violated at all. Although in the negative $v_g$ regime (denoted by coupling constants $\kappa_5$ to $\kappa_7$ in Fig. 4), the peak of the output pulse leaves the output before the peak of the reference pulse (of ring-less structure), it experiences a loss which makes its peak always below the rising edge of the reference pulse. This implies that the energy velocity is in fact positive, i.e. no energy can come out of the circuit before input energy going into the circuit. A more intuitive explanation is through the mathematical meaning of an analytic smooth pulse [11], like Gaussian pulse, which is approximated in the experiments. An analytic smooth function is (infinitely) differentiable, and hence able to be expressed in a Taylor’s expansion. Taylor’s expansion means that we are able to express the value of the future with values in the vicinity of a point in the past. Hence, in an analytic smooth function, the future is already known from the past. Hence, information velocity is still positive even when the $v_g$ is negative. In that condition, $v_g$ is no more the information velocity as already stated by Brillouin and Sommerfeld [8]. We can also intuitively see from Fig. 4 that the more the pulse is advanced, the heavier the distortion is. Distortion
implies the loss of information. The heaviest distortion happens when the negative $v_g$ is in its extreme point, i.e. at the critical coupling point (denoted by coupling constant $\kappa_4$), where the pulse apparently splits into two sub-pulses.

![Fig. 4. Direct experimental measured pulse behavior in positive and negative group velocity regimes of an integrated-optical ring-resonator.](image)

5. Concluding remarks

Although the negative $v_g$ phenomenon is not useful for signal processing application as a consequence of causality, the fact that it can be ‘slow’ (see arguments given in [4]) implies its role for sensitivity enhancement of novel optical sensor. This nice thing awaits for further explorations in the future.

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References


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Henri P. Uranus received Engineer (Ir.) degree in electrical engineering in 1987 from Trisakti University, Jakarta, the Master’s degree in optoelectronics in 1990 from the University of Indonesia, Jakarta, and Ph.D. degree in integrated optics in 2005 from the University of Twente, The Netherlands. From 1983 to 2001 he worked as an engineer for CV. Trans Komunikasi Data, Jakarta. From 1990 to 2001 and 1997 to 2001 he was also a part time junior lecturer with The Graduate Program on Optoelectronics and Laser Applications, the University of Indonesia and Dept. of Electrical Eng., the University of Pelita Harapan, respectively. In October 2001, he joined University of Twente, The Netherlands, as a Ph.D. student working on modeling of integrated optics. From 1 Feb. 2005 – 1 Feb. 2008, he was a post-doctoral researcher in Integrated Optical MicroSystems (IOMS) group, Dept. of Electrical Eng., the University of Twente, working on integrated-optical photonic sensor. From 11 Feb. 2008, he has been with the Dept. of Electrical Eng., University of Pelita Harapan, Indonesia as a lecturer. From 1 July 2008 he is the head of the Graduate Program in Electrical Engineering of the same university.

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