Direct Experimental Observation of Pulse Temporal Behavior in Integrated-Optical Ring-Resonator with Negative Group Velocity

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Abstract: *We report a direct experimental observation of pulse temporal behavior in an integrated optical two-port ring-resonator circuit as a function of coupling strength, including the transition across the critical coupling point. We demonstrate the observation of pulse 'advancement' in the negative v_g regime and pulse delay in the positive v_g regime. We also observed a smooth transition of the pulse shape from highly negative to highly positive v_g (or vice versa) through a pulse splitting phenomenon. The observed phenomena agree well to theoretical simulations.*

Introduction

The possibility to control the light group velocity (v_g) is currently an interesting research topic [1-6]. The capability to make light to travel with low v_g (e.g. much lower than light velocity in vacuum c in a so called slow-light phenomenon [1]), has raised many prospects in application areas of optical signal processing, light sources, optical sensing, etc. Besides, light can also be forced to travel with large v_g (e.g. larger than c), or even with negative v_g [1-6] either by engineering the material dispersion of the medium [2, 3] or the waveguide dispersion of the structure [4]. Although the phenomenon of negative v_g seems to be counter-intuitive as the peak of the output pulse appears earlier than the peak of the input pulse, its consistency with the causality principle has been experimentally verified [5].

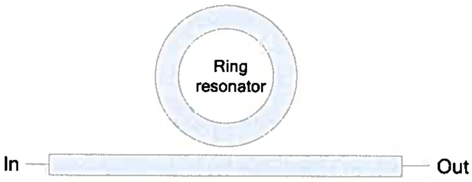

Fig. 1: A two-port ring-resonator circuit

It is well known that in lossy two-port ring-resonator (TPRR) circuits as shown in Fig. 1, in the under-coupling condition, light can have a negative group velocity [7] as shown in Fig. 2. Experimental [8] and theoretical [4, 6] studies on such a phenomenon has also been carried out. However, since it is understood that there will be no true negative delay (or 'advancement') in such a phenomenon (hence not so useful for signal processing applications), there is not much attention paid on experimental aspects for this phenomenon, compared to works on the same phenomenon using e.g. atomic gases [2] or fibers [3]. In fact, experiments using an integrated optical chip can be more handy and within the reach of many research groups. Also, we have theoretically showed [6] that such phenomenon has similar enhancing light-matter-interaction feature, like its slow-light counterpart, and therefore will be useful for applications like integrated-optical sensing. Consequently, further study and better understanding on such phenomenon from experimental aspect, are indispensable.

In this paper, we report the first direct experimental observation of pulse temporal behavior at the output of such a resonator for the regimes of negative and positive v_g, and transition between them across critical coupling point.

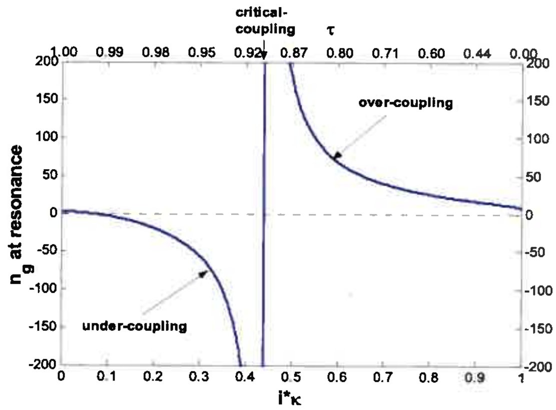

Fig. 2: The group index ($n_g \equiv c/v_g$) at resonant wavelength of a two-port ring-resonator circuit with parameters taken from the device under test discussed in this paper.

Experimental Set-up

For this experiment, we chose a TPRR which was originally designed for a delay line for optical beamforming applications [9]. The TPRR, which was designed and fabricated by Lionix BV [10], The Netherlands, has a controllable coupling constant and resonant wavelength through a thermo-optical mechanism. This Si_3N_4 based TPRR has a geometric ring round-trip length of 11916.4μm and supports a single q-TE mode with n_{eff} and $dn_{eff}/d\lambda$ (as calculated by a vectorial mode solver) of 1.6499 and $-0.1029\mu m^{-1}$, respectively. For a detailed description of the TPRR, please see the respective publication [9].

The experimental set-up is shown in Fig. 3. The measurement of pulse temporal behavior is basically carried out by sending a light pulse through the TPRR and recording its output pulse shape detected by an optical receiver using a fast oscilloscope (Agilent 54854A).

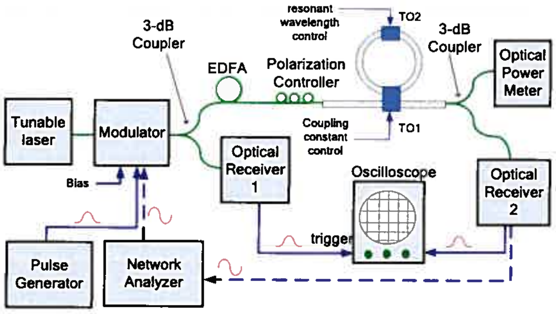

Fig. 3: The experimental set-up

For comparison between results of various settings of the TPRR, we need a reference time, which is measured at a well defined condition. For this purpose, we first tuned the laser to the resonant wavelength of the TPRR, and intensity modulated the light by a smooth pulse generated by a pulse generator, which has an internal electronic pulse shaper to control its rise and fall time. The pulse width is selected to be sufficiently small to be able to observe the phenomenon discussed in a later section. Then, we tuned the thermo-optical modulator TO1 (which controls the coupling constant) such that the output pulse amplitude (as detected by Optical Receiver2 and observed by the oscilloscope) is the lowest. Such condition is associated to a well defined critical coupling condition [6]. We then tuned TO2 (which controls the resonant wavelength) such that the ring is in an anti-resonant condition (a condition in the middle between two consecutive resonances). In such condition, the effect of the ring is minimal, and the delay is approximately the same as the one contributed by a similar circuit without the ring. We took this condition as a reference condition and refer to such fictitious ringless structure as the reference structure.

The output pulse shapes for various values of control to TO1 were recorded with TO2 set back to the TPRR resonant condition. Note that during these measurements, the oscilloscope was triggered by pulses detected by Optical Receiver1. Such triggering condition was kept the same during the whole measurements. Also note that an EDFA was inserted in the measurement set-up to compensate the loss of power in the set-up in order to capture a well detectable signal, while the polarization controller was used to condition the light to TE polarization before launched into the TPRR.

For the purpose of comparing the measurement results with theory, we also recorded the transmission spectra and the relative group delay spectra for each associated setting of TO1, and used these curves to retrieve the value of the coupling constants and ring loss through a curve fitting procedure. The transmission curves were measured by reading the output power while sweeping the tunable laser across the resonant wavelength. The relative group delay curves were measured by measuring the delay of the optical envelope signal using a modulation phase shift method [11, 12] while scanning the wavelength of the tunable laser. For this purpose, the pulse generator was disconnected and a vector network analyzer was introduced into the set-up (see the dashed-lines signal path in Fig. 3). In this set-up, the light was intensity modulated by a sine signal with modulation frequency of 50MHz with a bias and level set to produce undistorted output signal from Optical Receiver2. The vector network analyzer measured the delay between the sine signal it sent out to the modulator and the one it received from the Optical Receiver2, relative to a similar delay of the reference condition, which was measured earlier.

Results and Discussions

Fig. 4 shows the measured pulse temporal behavior for various values of coupling constant as set through TO1. For clarity, we also overlaid the picture with a pulse shape measured at the reference condition and draw a vertical dotted line to indicate its peak position which is referred to as $t = 0$. Since this reference condition approximately represents a condition for the reference ringless structure, the measured signal relative temporal position represents the 'advancement' or delay contributed by the ring resonator.

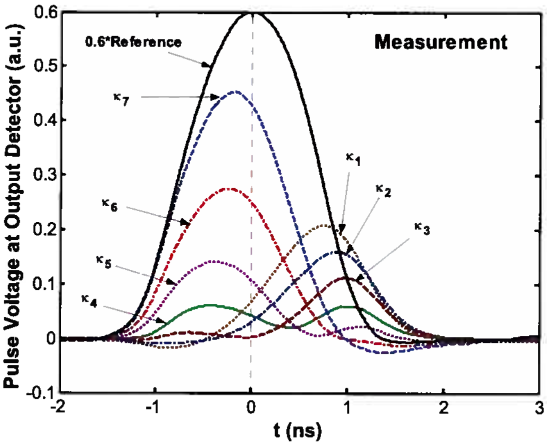

Fig. 4: The measured pulse temporal behaviour of the TPRR working in the positive and negative group velocity regime.

Fig. 4 clearly shows that at cross coupling constant values of κ_5, κ_6, and κ_7 (which were set through

TO1), the (main) peak of the output pulses of the TPRR comes out earlier than the peak of similar pulse for the reference structure. Such a pulse 'advancement' phenomenon is associated with a negative v_g condition. Inversely, for coupling constants of κ_1, κ_2, and κ_3, the (main) peak of the output pulses of the TPRR comes out later than the peak of similar pulse for the reference structure. Such pulse delay is associated with a positive v_g condition. Note that the higher the 'advancement' or delay, the smaller the pulse amplitude (or in other words, the larger the loss), indicating the more intense light-matter interaction in the ring. Hence, a highly negative v_g is in fact as potential as the positive one for applications that exploit light-matter interaction mechanism like optical sensing [6]. Fig. 4 also shows that the leading edge of the reference output pulse always appears before the peak of the weak output pulse of the TPRR, implying that the energy velocity contributed by the ring-resonator is always positive even in the negative v_g regime. Hence, there is no violation to the causality principles [1, 5].

The measured smallest output amplitude happens at a coupling constant of κ_4. This condition is associated with a critical coupling condition [6]. Fig. 4 shows that at this condition, the output pulse is highly distorted and split into two sub pulses, one with delay, and the other with 'advancement'. These two sub pulses represent the largest delay and 'advancement' achievable in the corresponding TPRR. We observed experimentally that the transition from the highly 'advancement' in the undercoupling condition to the highly delay in the over coupling condition acrossing this critical coupling point evolves in a very smooth manner, regardless on the fact that the group index at their resonant frequency changes abruptly as shown in Fig. 2. This smooth transition is due to the fact that the light is not single frequency anymore as a result of the modulation, and its Fourier spectrum is wide enough to cover the sharp feature in the ring response spectra. Experiencing such highly dispersive condition, makes the relative temporal positions of the frequency components of the signal to realign, change their superposed peak position, and split into two peaks at the extreme condition of the critical coupling. Such pulse splitting phenomenon suggests that there is a maximum achievable pulse delay and 'advancement' contributed by a single ring-resonator, bringing up the necessity of employing multiple cascaded ring-resonators for a time delay application [9] with relatively large delay. For the particular TPRR under test in this measurement, the maximum delay and 'advancement' deduced from Fig. 4 are 1.01 ns and 0.43 ns, respectively. The maximum achievable delay is always larger than the maximum achievable 'advancement' due to the fact that the group delay spectra corresponding to the undercoupling condition consists of both negative and positive group delay (see below) components, while for the overcoupling condition, such spectra only consists of positive delay. We should note that the pulse splitting condition could not be observed for a wide pulse which has Fourier spectrum of sufficiently narrow to avoid such highly dispersive condition. However, the delay and 'advancement' become not so pronounced anymore in such situation.

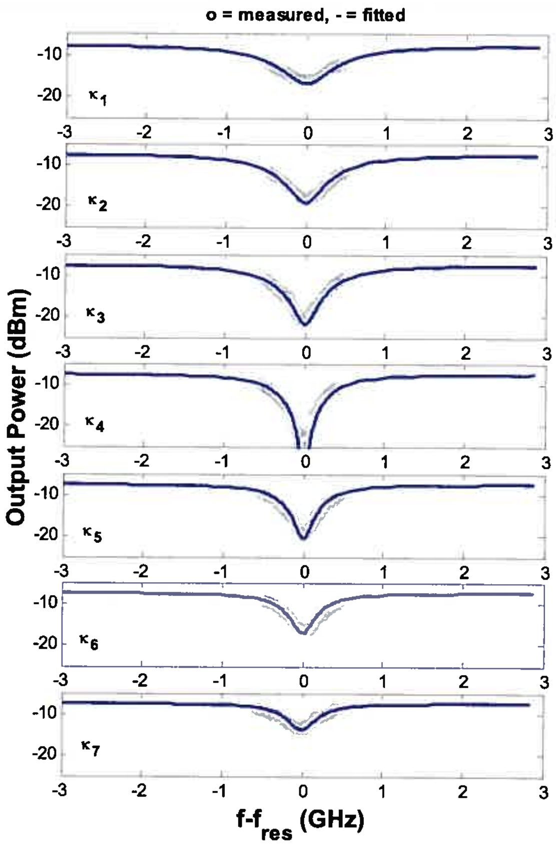

Fig.5: The measured output power (circles) and their best fit theoretical curves (solid lines).

Fig. 5 and 6 show the measured transmission spectrum and the relative group delay, together with their best fit theoretical curves that give minimum least squares error. In this fitting, the curves are treated altogether. Since there is limitation of the modulation phase shift method [12] and the wavelength scanning mechanism to capture extremely sharp features in the neighborhood of the critical coupling point, the measured data for this condition (κ_4) are excluded in the fitting for accuracy reasons. The measurement result for this coupling constant is assumed to be as the one of the critical coupling simply based on the fact that in the temporal measurement (Fig. 4) it exhibited the maximum loss. The best fit values of the structure parameters for κ_1, κ_2, κ_3, κ_5, κ_6, κ_7, and ring attenuation constant α are -0.5984i, -0.5542i, -0.5223i, -0.3581i, -0.3196i, -0.2695i, and 0.7842dB/cm, respectively. The coupling constant for critical coupling as calculated from α and ring round trip length is -0.44i.

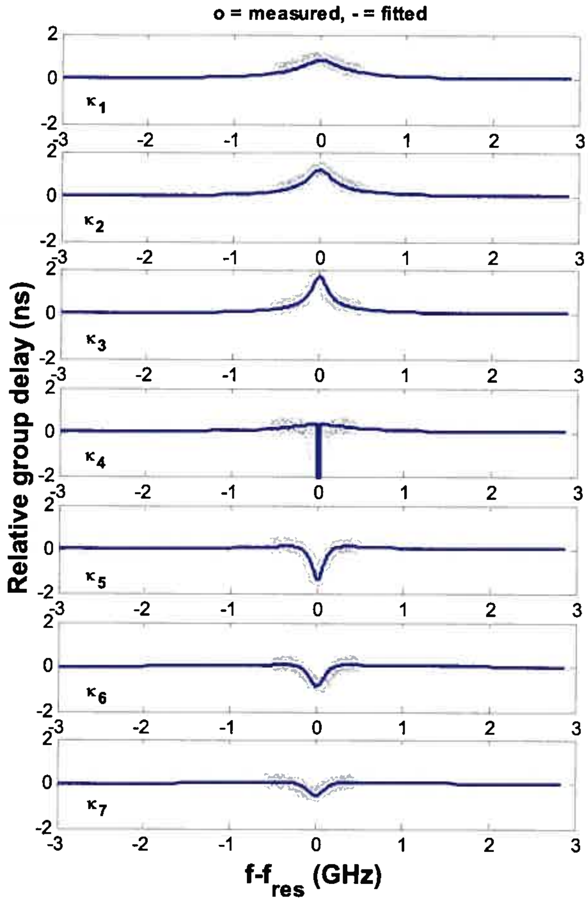

Fig.6: The measured relative group delay (circles) and their best fit theoretical curves (solid lines).

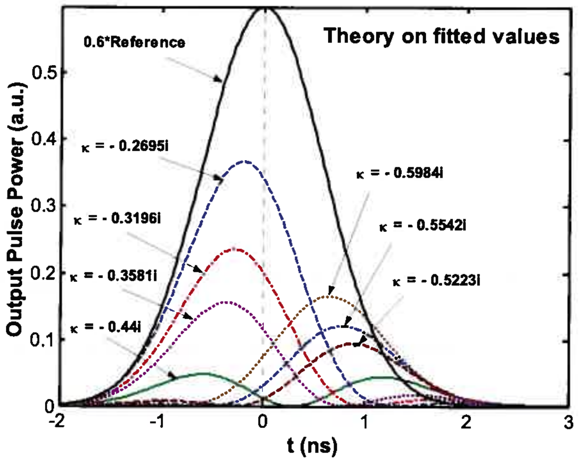

Fig. 7: The simulated pulse temporal behavior of the TPRR using the best fit values of the coupling constants and ring attenuation constant.

Using Fourier transform and the TPRR transfer function [6], we simulate the pulse temporal behavior in TPRR with the above mentioned best fit structure parameters. For this purpose, we took an input pulse with Gaussian amplitude which has a normalized power (or square of amplitude) profile that best fit to the measured reference pulse. Fig. 7 shows the simulated theoretical pulse temporal behavior on the fitted coupling constants and ring loss. These results show a good qualitative agreement between the observed and simulated pulse temporal behavior in the TPRR, including the pulse 'advancement', pulse delay, and pulse splitting phenomena.

Conclusions

We report a direct measurement of the pulse temporal behavior in a two-port ring-resonator circuit. We demonstrate the observation of the pulse 'advancement' under negative v_g and pulse delay under positive v_g conditions. We also observed that at the critical coupling point, the pulse is split into two sub pulses. We show that such a pulse splitting phenomenon facilitates a smooth transition between the high 'advancement' and the high delay condition acrossing the critical coupling point.

Acknowledgments

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