# Characterisation of microring resonator optical delay and its dependence on coupling gap using modulation phase-shift technique

L. Zhou, X. Sun, J. Xie, Z. Zou, L. Lu and J. Chen

The optical transmission of microring resonators is measured using a modulation phase-shift technique. The dependence of optical delay on the waveguide-to-resonator coupling gap is characterised. Experimental results reveal optical group delay can reach 270 ps when the critical coupling is approached in a high-Q microring resonator.

*Introduction:* Optical delay is one of the essential functions in optical signal processing [1]. Feed-forward and feedback structures are the two commonly used configurations, where optical delay is realised by routing to waveguides with different lengths or circulating inside a loop [2]. Among the various feedback structures, mirroring resonators have attracted great research interest owing to their simple configuration, high compactness, and compatibility with other functions [3–8]. Upon resonance, light is trapped inside the cavity, leading to a great enhancement of the optical delay. The microring resonators can be directly coupled with each other to form coupled-resonator optical waveguides [3, 5] or coupled with single or dual bus waveguides [4–8]. The single waveguide coupled microring resonator is the most fundamental building block for these complicated structures, which thus needs careful investigation both theoretically and experimentally. There are two primary factors that affect the optical transmission behaviours of waveguide-coupled microring resonators, namely the waveguide-to-resonator coupling coefficient and the resonator intrinsic loss. In [7], the microring optical delay performance was analysed by tuning the resonator loss with the free-carrier plasma dispersion effect. In this Letter, we focus on the waveguide-to-resonator coupling to investigate the dependence of optical time delay on the coupling gap using a modulation phase-shift technique.

*Device fabrication and characterisation:* Fig. 1 shows the scanning electron microscopy (SEM) image of the microring resonator on a silicon-on-insulator (SOI) substrate. The waveguide (both of the bus and ring waveguides) width is 0.5 µm and the height is 0.22 µm. The microring radius is 10 µm.

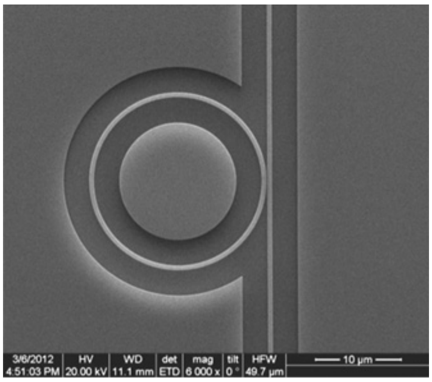

**Fig. 1** *Scanning electron microscopy image of microring resonator*

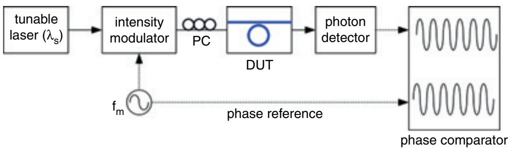

**Fig. 2** *Modulation phase shift measurement setup*

The microring resonator was patterned using deep-ultra-violet (DUV) photolithography and then dry-etched using inductively-coupled plasma (ICP) etching with an etched depth of 0.16 µm. The device was finally clad with a 1 µm-thick silicon dioxide layer using plasma-enhanced chemical vapour deposition (PECVD). To explore the effect of coupling gap on device performance, we designed a series of microring resonators with the gap size $g$ varying from 0.2 to 0.32 µm with steps of 0.03 µm. The resonators were put close enough on the same chip and fabricated together in the same run, so as to reduce fabrication-induced uncertainty.

The devices were characterised using an Agilent loss and dispersion analyser (86038B). Fig. 2 shows the experimental setup. A tunable laser source (with a scanning step of 10 pm) is modulated by an RF signal with frequency $f_m = 700$ MHz. The modulated light then passes through the devices and the output optical signal is detected and converted back to an electrical signal. The electrical signal is compared with the reference RF signal to extract the transmission loss and phase information. A polarisation controller is inserted before the devices to maintain a transverse-electric (TE) polarisation. Light is coupled into and out of the devices through on-chip waveguide inverse tapers with a coupling loss of 5 dB/facet. Optical group delay is calculated from the extracted phase of the intensity modulation waveform and is given as

$$\tau_g(\lambda) = \frac{\phi(\lambda) - \phi_r}{2\pi f_m} \tag{1}$$

where $\lambda$ is the optical carrier wavelength, and $\phi(\lambda)$ and $\phi_r$ are the phases of the modulation and reference waveforms, respectively. The group delay chromatic dispersion can then be calculated from the group delay:

$$D(\lambda) = \frac{d\tau_g(\lambda)}{d\lambda} = \frac{1}{2\pi f_m}\frac{d\phi(\lambda)}{d\lambda} \tag{2}$$

*Experimental results:* Fig. 3*a* shows the measured transmission spectra of the mirroring resonators with $g = 0.2$ to 0.32 µm. A small coupling gap helps to enhance the interaction between the bus and ring waveguides, thereby increasing the coupling coefficient. For the all-pass filter configuration, the competition between the coupling and the resonator loss determines the transmission performance. Three regimes can be discerned according to the coupling condition, namely over-coupling when coupling is stronger than resonator loss, critical-coupling when coupling and resonator loss are balanced, and under-coupling when coupling is weaker than resonator loss. As seen from Fig. 1*a*, with an increment in gap size, the resonance dip becomes sharper and the resonance extinction ratio increases to ~9 dB at $g = 0.29$ µm, suggesting it is closer to critical coupling. The resonance quality (Q)-factor is 64000 at $g = 0.29$ µm. When $g = 0.32$ µm, the resonance extinction ratio is still high (~10 dB), and yet it enters the under-coupling regime, as clearly shown by its phase response.

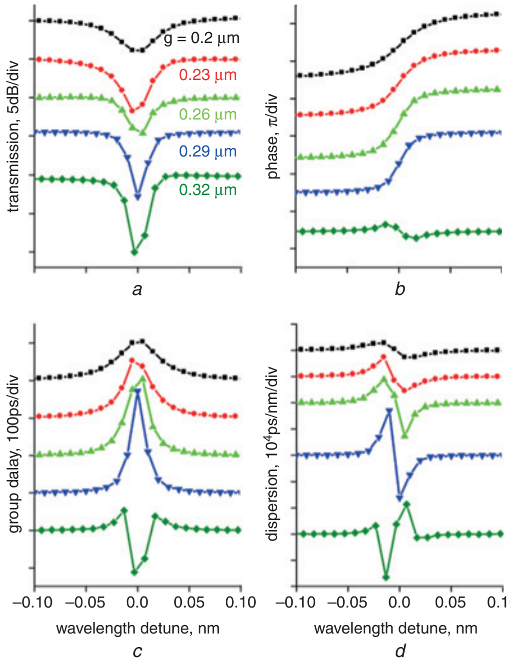

**Fig. 3** *Measured microring resonator transmission around resonance*

*a* Output power response
*b* Output phase response
*c* Group delay response
*d* Chromatic dispersion response

Fig. 3*b* shows the measured optical phases of the five microring resonators. It can be seen that the phase monotonically increases across resonance for $g = 0.2$ to $0.29\ \mu\text{m}$, while it has an abnormal drop for $g = 0.32\ \mu\text{m}$. These are the signs for resonators working at two different regimes with the former at over-coupling and the latter at under-coupling. Careful comparison of the first four phase curves reveals that the slope of the phase response becomes steeper when the gap increases.

The phase response is directly translated to the group delay response, as shown in Fig. 3*c*. The normal phase response in the over-coupling regime corresponds to group delay (or slow light), while the abnormal one results in group advance (or fast light). The resonator with $g = 0.29\ \mu\text{m}$ has the maximum group delay (relative to off-resonance) of 270 ps with a full-width-half-maximum (FWHM) bandwidth of 2.1 GHz. The resonator with $g = 0.32\ \mu\text{m}$ has a negative group delay of $-112$ ps with a bandwidth of 2.5 GHz.

The group delay has a symmetrical response around resonance, and hence the group delay chromatic dispersion is zero on resonance (Fig. 3*d*). Yet the dispersion becomes high when the wavelength slightly deviates from the resonance, which means the third-order dispersion is large. For example, the dispersion is $\pm 17000\ \text{ps/nm}$ (positive at shorter and negative at longer wavelength sides) for the resonator with $g = 0.29\ \mu\text{m}$, as shown in Fig. 3*d*. The under-coupling resonator has an inverse dispersion curve, originating from its distinct phase response (see Fig. 3*b*).

*Conclusion:* We have characterised the optical transmission responses of high-Q microring resonators using the modulation phase-shift technique. In particular, we explored the dependence of optical group delay on the waveguide-to-resonator coupling gap. It was found that, with an increment in gap size, the group delay gradually increases to 270 ps near critical coupling, and after that it becomes negative with group advance instead.

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One or more of the Figures in this Letter are available in colour online.

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