Simple and accurate measurements to characterize microdisk lasers for all-optical flip-flop operation

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Microdisk lasers have the potential to go down to a few microns in size and still operate in two stable states. But shape imperfection and sidewall roughness arising during the fabrication process, and reflections from various points in the device structure lead to the destruction of bistability and hence thwart flip-flop operation. Operating regimes of disk/ring lasers depend on conservative and dissipative coupling between clockwise and counterclockwise modes. Here we report simple and accurate measurements to calculate the conservative and dissipative coupling rates in order to characterize microdisk lasers heterogeneously integrated on to SOI for flip-flop operation.

Introduction

Semiconductor microdisk/ring resonators and lasers are the subject of intensive research owing to their compact size and on-chip high density integration potential. Microdisks/rings can be used to realize high speed all optical functionalities such as all-optical flip-flops (AOFFs), logic gates, switches, modulators, and (de)multiplexers. AOFFs based on disks/rings can serve as important memory elements to store information in all-optical signal processing. So far, the smallest and fastest AOFF had a total footprint of more than 700μm^2, consisting of coupled ring lasers with each ring having a 32μm diameter [1]. Single ring lasers have also been demonstrated as AOFF but with quite large diameter of 300μm [2]. It is a well known fact that the performance, in terms of switching speed, switching energy and total power consumption, of disk/ring based AOFFs can be enhanced with the reduction in their size. In reference [1], from simulations, authors predicted ultra-small and ultra-fast memory elements consisting of 3μm diameter disk lasers. Disks are better suited for realization of active photonic functionalities due to their low scattering loss and the availability of a compact electrical injection scheme as compared to rings. Bistability in single disks with diameter below 100μm [3] has not been possible due to an increased influence of the sidewall roughness with decreasing size, causing a detrimental effect on the bistability which ultimately prevents flip-flop operation. On this aspect theoretical investigations have been reported by different authors [4,5]. Also, there have been measurements of propagation loss in microring/disk resonators [6,7] where sidewall surface roughness induced backscattering accounts for either the most significant or a substantial contribution to the propagation loss. In reference [8], the transmission loss in Si/SiO_2 waveguide is measured where again sidewall roughness is the major source of loss. Transmission measurements [9] in passive silicon microdisks have shown lifting of the degeneracy between the clockwise (CW) and the counterclockwise (CCW) propagating whispering gallery modes (WGMs), due to scattering from disk sidewall surface roughness. No experimental investigations have been reported on surface roughness induced detrimental effects on the bistability in disk/ring lasers so far.

Heterogeneous integration of III-V materials on silicon-on-insulator (SOI) has emerged as a promising means to realize efficient active photonic functionalities. Heterogeneous integration allows to realize a high optical confinement factor desirable for efficient lasers. Here, we report accurate measurements on the detrimental effect of sidewall roughness for AOFF operation with InP-InGaAsP disk lasers heterogeneously integrated on to SOI.

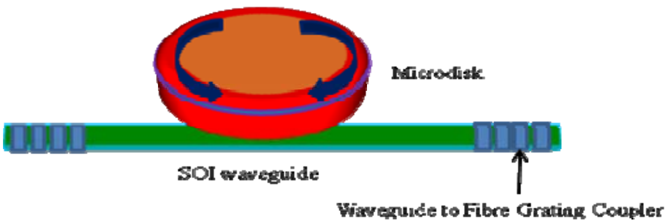


Figure 1. Schematic of a microdisk laser

Measurement Technique

The device design used in our experiment is shown in Figure 1. The microdisk is vertically coupled to a straight SOI waveguide to couple light out of the microdisk by evanescent coupling. Grating couplers are used to couple light from waveguide to a single mode fibre. In microdisk resonators/lasers each longitudinal mode is doubly degenerate, one counter propagating to the other. These are usually named as CW and CCW modes. Due to inevitable imperfections in the fabrication process, there always exists surface roughness on the microdisk sidewall which breaks the azimuthal symmetry and results in removal of the degeneracy of CW and CCW modes, and also causes scattering of these WGMs confined along the circumference of the disk. Scattered light couples either in to a radiation mode or the counter propagating mode [5]. Excitation of the counter propagating mode by back-reflected light prevents unidirectional behaviour which is necessary for flip flop operation. Removal of the degeneracy is manifested in the splitting of the resonance. This splitting is usually too

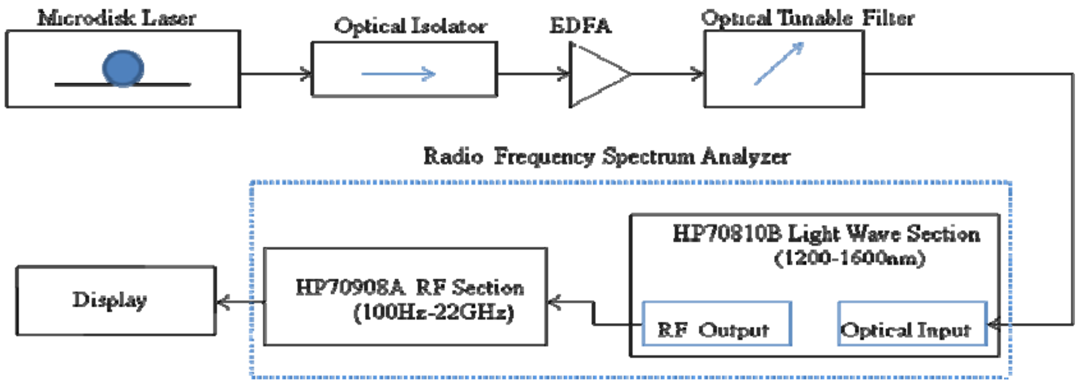
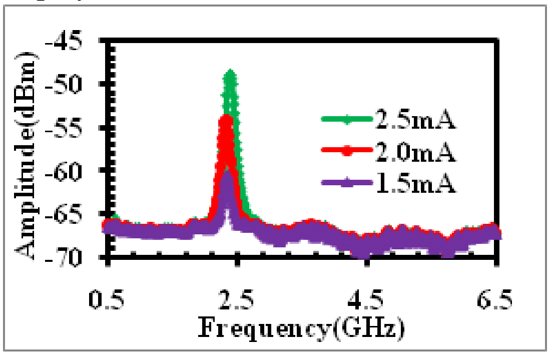


Figure 2. Experimental set-up for beat frequency measurements

small to be measured with an optical spectrum analyser due to the limited resolution, but it gives a beat in the total power measured by a photodetector and can be measured using an RF spectrum analyser. Analysis of the beat frequency can provide the accurate and important information about the possibility of flip-flop operation in microdisk lasers. This is discussed in detail in section III. A schematic of the experimental set-up employed for beat frequency measurements is shown in Figure 2. As the output power of the microdisk laser coupled to the fibre is very low (some hundreds of nano watts), it is amplified with an erbium doped fiber amplifier (EDFA). An optical isolator is placed in between the microdisk laser and the EDFA to avoid coupling of amplified spontaneous emission noise back to the microdisk laser which can destabilize it. The EDFA is followed by an optical tunable filter, tuned at the wavelength of the microdisk laser output light, to suppress spontaneous emission noise generated by the EDFA. The amplified and noise suppressed light is fed to the HP70810B Light Wave Section of an RF spectrum analyser which converts the optical input into a radio frequency (RF) signal. This RF signal is given as an input to the HP7090 8A. Finally the beat frequency of the CW and CCW modes appears as a resonance in the RF spectrum and is seen on display screen.



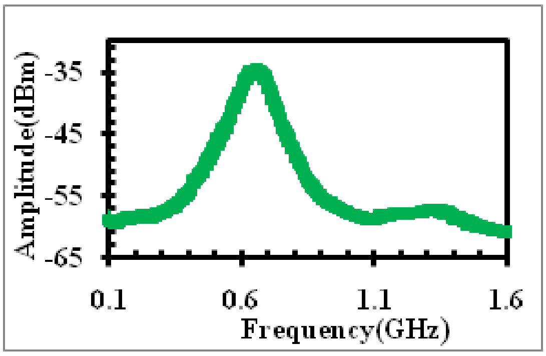


Figure 3. RF Spectra for MD1

Figure 4. RF Spectrum for MD2 at 2.5mA

Results and Discussion

Following the procedure discussed in section II, we measured the RF spectra of the TE light output of two 10µm diameter microdisk lasers denoted as MD1 and MD2. They are shown in Figures 3 and 4 respectively. One can clearly notice the resonance due to coupling between CW and CCW modes in these figures. From our calculations we found that the resonance frequency itself corresponds to K_c/π with K_c the conservative coupling per unit time, while the 6dB bandwidth of the resonance corresponds to $2K_d/\pi$ with K_d the dissipative coupling per unit time. RF spectra at different pump currents, shown in Figure 3, are measured to eliminate the possibility of measuring relaxation oscillation frequencies.

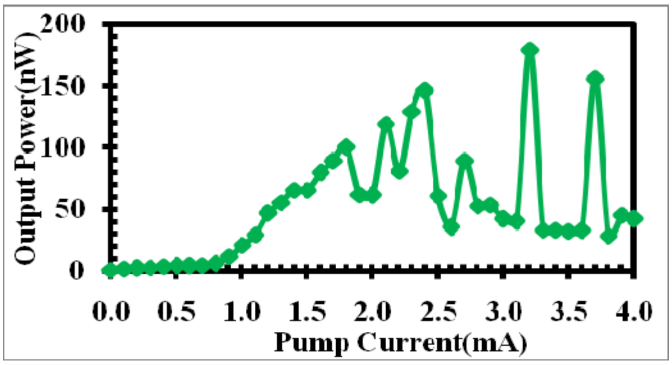


Figure 5. LI curve for MD2

It is clear from Figure 3 that the resonance peaks stay at the same frequency with negligibly small deviation with variation in the pump current. For a microdisk laser to operate unidirectionally, and hence show switching between CW and CCW modes under external optical pulse injection, a small value of conservative coupling rate (K_c) is required irrespective of the value of the dissipative scattering coefficient (K_d) but both the values should have same order of magnitude. For other operating regimes (bidirectional alternate oscillations and bidirectional continuous wave) certain combinations of K_c and K_d are required. This is discussed in detail in reference [10] through simulations and fitting procedure. For the microdisk laser MD1 at pump current of 2.5mA, K_c and K_d values are $7.5X10^9 s^{-1}$ and $2.36X10^8 s^{-1}$ respectively and the laser is found to operate in continuous wave bidirectional regime. In the case of MD2, these values are $2.08X10^9$ s^{-1} and $2.51X10^8$ s^{-1} for the same pump current. The value of K_c of MD2 is lower by a factor of 3.6 as compared to that of MD1. There are sudden transitions in the LI curve of MD2, shown in figure 5, which indicate the possibility of unidirectional behaviour. This is consistent with the fact of lower value of K_c. Unidirectional behaviour is not very much pronounced due to the low output power. In conclusion, we have used a very simple and accurate technique to characterize microdisk lasers for flip flop operation. This technique is a better alternative to numerical simulations and fitting procedure to find coupling rates.

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