Switchable in-line monitor for multi-dimensional multiplexed photonic integrated circuit

Guanyu Chen, Yu Yu,* Mengyuan Ye, and Xinliang Zhang
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
*yuyu@mail.hust.edu.cn

Abstract: A flexible monitor suitable for the discrimination of on-chip transmitted mode division multiplexed (MDM) and wavelength division multiplexed (WDM) signals is proposed and fabricated. By selectively extracting part of the incoming signals through the tunable wavelength and mode dependent drop filter, the in-line and switchable monitor can discriminate the wavelength, mode and power information of the transmitted signals. Being different from a conventional mode and wavelength demultiplexer, the monitor is specifically designed to ensure a flexible in-line monitoring. For demonstration, three mode and three wavelength multiplexed signals are successfully processed. Assisted by the integrated photodetectors (PDs), both the measured photo currents and eye diagrams validate the performance of the proposed device. The bit error ratio (BER) measurement results show less than 0.4 dB power penalty between different modes and ~2 dB power penalty for single wavelength and WDM cases under 10⁻⁹ BER level.

©2016 Optical Society of America

OCIS codes: (130.0130) Integrated optics; (250.5300) Photonic integrated circuits; (060.4230) Multiplexing; (230.5160) Photodetectors; (120.4630) Optical inspection.

References and links

1. D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibres,” Nat. Photonics 7(5), 354–362 (2013).
2. P. J. Winzer, “Making spatial multiplexing a reality,” Nat. Photonics 8(5), 345–348 (2014).
3. L.-W. Luo, N. Ophir, C. P. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergmen, and M. Lipson, “WDM-compatible mode-division multiplexing on a silicon chip,” Nat. Commun. 5, 3069 (2014).
4. T. Uematsu, Y. Ishizaka, Y. Kawaguchi, K. Saitoh, and M. Koshiba, “Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission,” J. Lightwave Technol. 30(15), 2421–2426 (2012).
5. W. Chen, P. Wang, and J. Yang, “Mode multi/demultiplexer based on cascaded asymmetric Y-junctions,” Opt. Express 21(21), 25113–25119 (2013).
6. D. Dai, J. Wang, and Y. Shi, “Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light,” Opt. Lett. 38(9), 1422–1424 (2013).
7. Y. Ding, J. Xu, F. Da Ros, B. Huang, H. Ou, and C. Peucheret, “On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer,” Opt. Express 21(8), 10376–10382 (2013).
8. J. B. Driscoll, R. R. Grote, B. Souhan, J. I. Dadap, M. Lu, and R. M. Osgood, “Asymmetric Y junctions in silicon waveguides for on-chip mode-division multiplexing,” Opt. Lett. 38(11), 1854–1856 (2013).
9. H. Qu, H. Yu, T. Hu, G. Jiang, H. Shao, P. Yu, J. Yang, and X. Jiang, “Silicon mode multi/demultiplexer based on multimode grating-assisted couplers,” Opt. Express 21(15), 17904–17911 (2013).
10. J. Xing, Z. Li, X. Xiao, J. Yu, and Y. Yu, “Two-mode division multiplexer and demultiplexer based on adiabatic couplers,” Opt. Lett. 38(17), 3468–3470 (2013).
11. B. A. Dorin and W. N. Ye, “Two-mode division multiplexer in a silicon-on-insulator ring resonator,” Opt. Express 22(4), 4547–4558 (2014).
12. N. Hanzawa, K. Saitoh, T. Sakamoto, T. Matsui, K. Tsujikawa, M. Koshiba, and F. Yamamoto, “Mode multi/demultiplexing with parallel waveguide for mode division multiplexed transmission,” Opt. Express 22(24), 29321–29330 (2014).
13. J. Wang, P. Chen, S. Chen, Y. Shi, and D. Dai, “Improved 8-channel silicon mode demultiplexer with grating polarizers,” Opt. Express 22(11), 12799–12807 (2014).
With the rapid development of information society, the demand for larger optical communication capacity is more and more urgent. Multidimensional multiplexing technology is thus adopted to increase the transmission capacity both in fibers and integrated chips [1–3]. Compared with the fibers, silicon on insulator (SOI) platform featured with low cost and easy compatibility with complementary metal oxide semiconductor (CMOS) technology has attracted great attention during the past years, and the on-chip multidimensional multiplexing were widely studied in particular. The mode division multiplexing (MDM) [4–13], wavelength division multiplexing (WDM) [14] and the combination of MDM and WDM [3,15–17] have been demonstrated extensively. However, most of the reported multiplexing technologies in silicon focus on increasing the capacity [6,13,15] and optimizing the structures to realize better performance [3,4,7–12,16–18], and the advanced functionalities have not been investigated.

For the future high-capacity optical communication network containing the multidimensional multiplexed signals, the optical performance monitoring (OPM) is desirable for fault management and quality-of-service (QoS) monitoring [19–25]. However, most of the proposed monitoring schemes are based on the fiber network [19–22]. For the large capacity and reconfigurable on-chip system, the information of the multiplexed signals and the uniformity of individual channels are necessary to know for the purpose of feedback control. In addition, for silicon platform, the devices are sensitive to fabrication tolerances and environmental fluctuations, and the transmitted signals will thus be affected, especially when many photonic components are integrated on a single chip [23–25]. As a result, the on-chip monitoring for integrated photonic circuits is greatly needed. However, the reported on-chip schemes only monitor the average power for transmitted signals, and additional pilot tones...
should be applied separately on each channel if the power of specific channel needs to be monitored. More importantly, the detailed and complete information of signals loaded on each multiplexed channels cannot be identified and distinguished. With the increasing usage of multiplexing technology for photonic integrated circuit, the in-line and switchable on-chip monitor with diversified functions is greatly desirable.

Therefore, a flexible in-line monitor suitable for on-chip multidimensional multiplexed signals discrimination is proposed and experimentally demonstrated. To be noted, the ample information of the transmitted signals can be successfully extracted based on the proposed device and this is compatible with extra processing functionalities demonstrated in other monitoring schemes. Much more processing functionalities can be further realized if necessary. The on-chip monitor consists of a span of multimode waveguide, two micro-ring resonators (MRRs) and germanium photodetectors (Ge PDs). The mode information is distinguished through the mode dependent coupling based on the phase matching of waveguides with different widths, while the wavelength information is discriminated based on the drop filtering of the thermally tuned MRR. As the MRR resonance wavelength can be easily aligned through the thermal heater, the in-line monitor is very flexible and can be switched between the states of monitoring and non-monitoring. Being different from a conventional mode and wavelength demultiplexer [3], the monitor is specifically designed to ensure a partial power extraction for in-line monitoring. Both the measured photo currents and eye diagrams validate the successful monitoring performance of the proposed devices for the WDM-MDM signals. The bit error ratio (BER) measurement is also carried out to quantitatively characterize the performance of the proposed monitor. The measured power penalty is less than 0.4 dB between different transverse electric (TE1 and TE2) modes and about 2 dB between single wavelength and WDM cases under $10^{-9}$ BER level.

2. Operation principles

The schematic diagram of the proposed on-chip monitor is shown in Fig. 1(a). The transmitted WDM-MDM signals in the multimode waveguide can be optionally discriminated when passing through the in-line monitor. The principle for the discrimination is based on the selective coupling between the multimode waveguide and the MRRs. Only when the mode phase matching condition is met and the resonance wavelength of the MRR matches that of the channel (Monitor-on), the specific signal will be dropped by the corresponding MRR, and thus the power, mode and wavelength information can be obtained from the output of the detectors.
As the three modes (TE₀, TE₁ and TE₂) and three wavelengths multiplexed signals shown in Fig. 1(a), two MRRs with different waveguide widths are designed to extract the transmitted signals for monitoring. Here, the TE₂ mode will be dropped and detected by the first MRR (MRR1) and PD1, while the TE₁ mode will be processed by the MRR2 and PD2. Therefore, by recording the output power of PD1 and PD2, which kinds of high order modes are involved can thus be known. To simplify the fabrication, the MRR for TE₀ was not included in this proof-of-concept demonstration, since an extra lithography and etching layer or structure is necessary to engineer the effective index for TE₀ extraction. On the other hand, some information of the TE₀ mode (for instance the power) can still be distinguished by comparing the total power of the transmitted signals and the monitored power of TE₁ and TE₂ modes. The integrated Ge PDs are used for transforming the optical signal into electrical signal, which simplifies the subsequent measurement by benefitting from the mature processing in electrical domain. The wavelength discrimination can be achieved by controlling the resonance wavelengths of the MRRs through the thermo-optic effect of the silicon waveguide. Furthermore, the proportion of the detected mode and wavelength can be calculated from the detected power, given that the MRR coupling ratio and responsivity of the PDs are known beforehand.

To validate its performance, the photonic integrated circuit contains a complete mode and wavelength multiplexer/de-multiplexer based on MRRs, as well as the on-chip monitor is proposed. The structure and parameters are described in Fig. 1(b). The multiplexer and demultiplexer are exactly the same due to the reciprocity. Taking the TE₁ mode signal at \( \lambda_1 \) for example, the original TE₀ mode signal at \( \lambda_2 \) is first injected into port IN2. It will be...
converted to TE_1 mode through the MRR based mode converter, and then transmitted across the cascaded tapers and multimode waveguides. The tapers are utilized to connect different waveguides supporting different order of modes. In the second MRR of the monitor, the TE_1 mode at \( \lambda_2 \) will be dropped and detected by PD2 if the resonance wavelength is aligned to \( \lambda_2 \), while there is nothing in PD1 due to the phase mismatch. Therefore, by comparing the photo currents of the two PDs, the TE_1 and TE_2 modes at different wavelengths can be discriminated. Moreover, the optical power of TE_1 and TE_2 modes can also be estimated since the responsivity of the Ge PD is a constant.

It is worth noting that the proposed monitor is a flexible scheme because the transmitted WDM-MDM signals will not be affected if the MRR resonant wavelength is detuned (Monitor-off). When the monitor is switched to “on” state, the proportion of the dropped power can be designed as needed, given that the sensitivity of the PDs are known. The switch time is determined by the thermal tuning rate, which is estimated to be about sub-millisecond. Although only three wavelengths and three modes are involved for demonstration, it is easy to extend the proposed scheme to accommodate more wavelengths and modes, by cascading more MRRs with carefully engineering the effective index of the waveguide.

3. Design and fabrication

Compared with MRR based multiplexer in [3], the modified ridge waveguides are used here to improve the coupling strength of all the non-racetrack MRRs for the proposed on chip circuit. The etch depth for the ridge waveguide is 130 nm. In the multiplexing/demultiplexing parts, based on our previous work [17], the width of single-mode waveguide is chosen as 500 nm, while the multimode waveguide are designed as 1.1 and 1.7 \( \mu \)m for TE_1 and TE_2 mode, respectively. For all the MRRs in the multiplexing/demultiplexing parts, the radius and gap are optimized to be 50 and 0.3 \( \mu \)m after weighing the coupling efficiency and the full width half maximum of the MRRs.

Although the proposed monitor is also based on the selective phase matching condition, it is inherently different from the demultiplexer part in Fig. 1(b). For a demultiplexer, all the MRRs are the same (diameter, width, gap, etc.) while the widths of the straight waveguides are varied to fulfill phase matching condition for different modes cases. The segmented waveguides with different widths are then connected through the tappers. Different segmented waveguides support different modes. In principle, the critical coupling for the MRR is expected. By contrast, for the proposed monitor, one uniform multimode waveguide (supporting all the modes transmission) is used for all the modes cases. The critical coupling for the MRR is not necessary. Only by doing this, the monitoring has little effect on the through traffic. Accordingly, the parameters of the MRRs are differently and specially chosen for different modes cases to realize only one mode satisfies the partial extraction condition and thus be distinguished. The differences can also be understood from the simulated effective index, as shown in Fig. 2(a). The effective indices in the case of demultiplexer are all targeted to 2.57 for all the waveguide, ensuring demultiplexing the desired modes from waveguides with different widths. On the other hand, the effective indices in the case of monitoring are designed to 2.37 and 2.63, ensuring partially extracting the desired modes from a same multimode waveguide. Considering this, the widths of the multimode waveguide and the MRR have to be carefully chosen. According to Fig. 2(a), if the width of the multimode waveguide is chosen to be 1.3 \( \mu \)m, only TE_1 mode will satisfy the phase match condition and it can be dropped provided the width of the MRR2 waveguide is designed to be 0.6 \( \mu \)m. By contrast, only TE_2 mode will be dropped when the width of the MRR1 is chosen to be 0.33 \( \mu \)m. In this case, the multimode waveguide needs to be tapered from 1.7 to 1.3 \( \mu \)m.
Although other width combinations theoretically satisfy the phase matching condition, the performance will not be as good as these values. If the width of the multimode is larger than 1.3 μm, the width of the MRR for TE₁ mode monitoring should be correspondingly increased from 0.6 μm. However, waveguide wider than 0.6 μm features multimode characteristics, and this will cause difficulty in designing the bend waveguide of the MRR2. If the width of the multimode is narrower than 1.3 μm, the width of the MRR for TE₂ mode monitoring should be correspondingly decreased from 0.33 μm. The transmission loss will be however increased significantly. Under the phase matching condition, the possible width combinations of the MRRs and the transmission multimode waveguide are shown in Table 1. After a comprehensive consideration, the width of the multimode, the MRRs for TE₁ and TE₂ monitoring are chosen to be 1.3, 0.6 and 0.33 μm for demonstration. The gaps between the MRRs and the multimode are 0.3 for TE₁ and 0.5 μm for TE₂ mode. The radii are 50 μm for both MRRs. The multimode waveguides with different widths are connected through the adiabatic tapers with length of 150 μm.

Table 1. The width combinations of the MRRs and the transmission multimode waveguide under the phase matching condition.

| Multimode width (μm) | Width of the MRR for TE₁ monitoring (μm) | Width of the MRR for TE₂ monitoring (μm) |
|----------------------|----------------------------------------|----------------------------------------|
| 1.2                  | 0.55                                   | <0.3                                   |
| 1.3                  | 0.6                                    | 0.33                                   |
| 1.4                  | 0.64                                   | 0.37                                   |
| 1.5                  | 0.71                                   | 0.41                                   |
| 1.6                  | 0.75                                   | 0.45                                   |
| 1.7                  | 0.8                                    | 0.48                                   |
The proposed photonic circuit containing the on chip monitor is fabricated on the 220 nm thick silicon on insulator (SOI) wafer with 2 μm buried oxide (BOX) at the Institute of Microelectronics (IME) in Singapore. The 70 nm etched 1D granting coupler is adopted for vertical coupling. The 10 μm long, 500 nm thick and 5 μm wide Ge absorption region is grown on the 130 nm etched silicon ridge waveguide and the boron and phosphorous doping was used to create the vertical PIN junction. On the top of each MRR, the TiN heater is deposited for resonance wavelength aligning. The cross section of the devices and the final microscopic image of the fabricated circuit are shown in Figs. 2(b) and 2(c), respectively.

4. Device characterization

Firstly, the transmission spectra at the three demultiplexing output ports (OUT1, OUT2 and OUT3) are measured, by controlling the monitor working at the monitor-off state. The results are shown and summarized in Fig. 3 and Table 2, respectively. The measured extinction ratio (defined as the ratio of the peak power to the minimum power of the desired signal) is larger than 36.5 dB and the mode crosstalk (defined as the ratio of the desired signal power to the interfering channels’ power [3]) is lower than –20 dB for all the modes. The total insertion loss of the multiplexing and demultiplexing MRRs are about 3.2, 4.1 and 5.2 dB for TE0, TE1 and TE2 modes, respectively. All the MRRs for mode multiplexing/demultiplexing show a uniform free spectra range (FSR) of 2 nm and a FWHM of about 0.07 nm.

![Fig. 3. The transmission spectra of the MRR based mode mux/de-mux. The measured transmission spectra at the three corresponding output ports when the signals injected on (a) port IN1, (b) port IN2 and (c) port IN3.](image)

| Number   | IL(dB) | FSR(nm) | FWHM(nm) | ER(dB) |
|----------|--------|---------|----------|--------|
| IN1-OUT1 | −3.2   | −2      | −0.09    | >36.5  |
| IN1-OUT2 | <−37   | /       | /        | /      |
| IN1-OUT3 | <−34   | /       | /        | /      |
| IN2-OUT1 | <−35   | /       | /        | /      |
| IN2-OUT2 | −4.1   | −2      | −0.07    | >37.5  |
| IN2-OUT3 | <−32   | /       | /        | /      |
| IN3-OUT1 | <−35   | /       | /        | /      |
| IN3-OUT2 | <−33   | /       | /        | /      |
| IN3-OUT3 | −5.2   | −2      | −0.056   | >36.7  |

To validate the performance of the on-chip monitor, the photo currents of the Ge PDs are then measured. The optical power and wavelength of the input continuous wave (CW) light are 11 dBm and 1550 nm, and the measured photo currents are shown in Table 3. For TE0 mode inputs from port IN1, the phase matching condition cannot be satisfied and the measured photo currents from PD1 and PD2 are very weak. For TE1 mode inputs from port IN2, the significantly large currents are observed from PD2 since only TE1 can be extracted to PD2. By contrast, the large current is obtained from PD1 for TE2 mode inputting from port IN3.
IN3. The bandwidth of the Ge PD is measured to be 36 GHz under 3 V reverse biased voltage based on the reference structure. The measured spectra are also recorded at the demultiplexing part for three modes when the two monitor MRRs are aligned/detuned to the desired wavelength, with results being shown in Fig. 4. For TE0 mode, no obvious degradation of the spectra can be observed. For TE1 mode, about 4.98 dB optical power difference is observed between the detuned (monitor-off) and aligned (monitor-on) cases, corresponds to about 68.23% optical power for TE1 mode in the multimode being dropped. The value is 3.65 dB (56.87%) for TE2 case. As the responsivity is about 0.78 A/W for the Ge PD, the optical power for the TE1 and TE2 modes in the multimode waveguide before the tapping can be estimated as 3.35 and 2.78 dBm, respectively. To be noted, the proportion of the dropped power can be changed according to different requirement, through designing the gap of the MRR and the multimode waveguide. The accuracy and reproducibility of the tuning of the resonance of the MRR is important to ensure a good and stable monitoring. These can be ensured by accurately fabrication and carefully control the thermal tuning. The accuracy and reproducibility within a reasonable range had been experimentally validated by the reference MRR. The results indicate the selective and flexible monitoring capability of the proposed inline scheme.

![Image](https://via.placeholder.com/150)

**Fig. 4.** The measured transmission spectra for (a) IN1-OUT1, (b) IN2-OUT2 and (c) IN3-OUT3 when the MRRs in the monitor part are detuned and aligned for detection of PD1 and PD2 (The inset shows the zoom-in details of the transmission spectra at the resonance wavelength).

**Table 3.** The measured photo currents of the Ge PD for signal injection from three different ports.

| Input ports | Current at PD1 (mA) | Current at PD2 (mA) |
|-------------|---------------------|---------------------|
| IN1         | 0.00295             | 0.0035              |
| IN2         | 0.00867             | 1.15                |
| IN3         | 0.842               | 0.00495             |

The WDM-MDM non-return-to-zero (NRZ) signals are then used to test the proposed monitor. The experimental setup is shown in Fig. 5(a). Three CW lights (W1: 1548.6 nm, W2: 1549.3 nm and W3: 1550 nm) are combined and modulated via the modulator. Two arrayed waveguide gratings (AWGs) and three tunable optical delay lines (ODLs) are used to de-correlate the WDM signals, by performing the de-multiplexing, the delaying and the re-multiplexing respectively. Then, the obtained NRZ signals with pseudo random bit sequence (PRBS) of $2^7-1$ at 10 Gb/s are coupled into the chip and the polarization controllers (PCs) are used to optimize the modulation efficiency and maximize the coupling efficiency. The DC bias is applied on the heater to align the resonance wavelength of the MRR, and a reference is made to ensure the relevant MRRs are all aligned. In the experiment, all the three wavelength signals are input on one spatial mode at a time. Then the signal at specific wavelength and mode is extracted by tuning the resonance of the MRR. The output light at the demultiplexing part is injected into the optical spectrum analyzer (OSA) and power meter (PM) for
characterization. The output electrical signals of the Ge PDs in the monitor part are collected using the ground-signal-ground (GSG) probe, through which the reverse bias is also applied using the bias-T. The monitored electrical signals are injected into the digital communication analyzer (DCA) and error analyzer (EA) for analyzing.

Fig. 5. (a) Experimental setup (BPG: Bit pattern generator; MZM: Mach-Zehnder modulator; EDFA: Erbium-doped optical fiber amplifier). The measured optical spectra at the demultiplexing port (b) OUT1, (c) OUT2 and (d) OUT3 for three different wavelengths are aligned with the demultiplexing MRR respectively. (Red: W1, Green: W2, Blue: W3, Black: WDM signals. The input WDM signals spectrum (black line) and the aligned spectra (Red, Green and Blue lines) at the demultiplexer part are measured under different power levels.). (e) The measured 10 Gb/s eye diagrams by the two Ge PDs (PD1 and PD2) in the monitor part when the MDM-WDM signals with three different wavelengths (W1, W2 and W3) are injected into port IN1, IN2 and IN3, respectively. (f) The measured 10 Gb/s BER results for single wavelength and WDM cases (one of the WDM channel is chosen) when the MDM-WDM signals input into port IN2 and IN3.

The measured optical spectra at the demultiplexing ports (OUT1, OUT2 and OUT3), for the cases of inputting from IN1, IN2 and IN3, are presented in Figs. 5(b) to 5(d). All the inputs are three wavelengths on TE0, and the monitor is adjusted to monitor-off state. Taking Fig. 5(b) as a representative, when TE0 signals at three wavelengths are inject from port IN1, the signals at different wavelength can be detected one by one as the different colors indicated, through the thermal tuning of the MRRs in the demultiplexing part. The conclusions are same for TE1 and TE2 cases, validating the successfully MDM and WDM signals processing capability and good performance of the multiplexer and demultiplexer.

Then, the monitor is adjusted to monitor-on state, and the eye diagrams are measured and presented in Fig. 5(e). When the signals are input from port IN1, no signal is detected by the Ge PDs regardless of the wavelength since none of the MRR is designed to tap the TE0 mode. When the signals are injected from port IN2, the PD2 shows clear eye diagram for all the
three wavelengths because the phase match is only satisfied for TE$_1$ mode. Meanwhile, the PD1 detects nothing since it only works for TE$_2$. In the same way, clear eye diagrams are obtained from PD1 for all the three wavelengths and nothing is observed for PD2 when the signals are injected from port IN3, which validates the successful discrimination for TE$_2$ mode. The different rising time of the monitored eye diagrams (compared with the original ones) are caused by the limited FWHM of the MRRs, and it can be improved by redesigning the MRR.

Finally, the BER measurements are performed to quantitatively characterize the performance of the proposed on-chip monitor. As there is no special monitoring MRR and PD designed for TE$_0$ mode, only results for TE$_1$ and TE$_2$ are measured. The measurements are performed for single wavelength (1550 nm) and WDM operations, respectively, as the results in Fig. 5(f) shown. For WDM case, one result of three input wavelengths is adopted for simplification. Less than 0.4 dB power penalty is observed between TE$_1$ and TE$_2$ mode for both single wavelength and WDM cases. The power penalty is about 2 dB between the single wavelength and WDM cases for both modes, indicating a reasonable performance on crosstalk. Such a crosstalk can be attributed to the wavelength crosstalk between the three uncorrelated WDM channels.

5. Conclusions

In conclusion, we have proposed and fabricated a flexible on-chip and in-line monitor suitable for WDM-MDM transmitted signals. The monitor can be switched between monitor-on and monitor-off states. The information of mode, wavelength and power can be distinguished. For validation, the proposed monitor combined with the wavelength and mode multiplexing/demultiplexing system is fabricated. According the measured photo currents and eye diagrams, the complete information of mode, wavelength and power are successfully distinguished. The measured BER results show that the power penalty is tolerable either between different modes or between single wavelength and WDM cases. It is promising that the proposed flexible monitor can be placed in the on-chip interconnection systems, since the monitoring function is switchable and has little influence on the transmitted signals.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (61475050 and 61275072); the New Century Excellent Talent Project in Ministry of Education of China (NCET-13-0240) and the Fundamental Research Funds for the Central Universities (HUST2015TS079).