Temperature-insensitive refractometer based on an RI-modulated singlemode-multimode-singlemode fibre structure

PENGFEI WANG,1,2 SHUO ZHANG,2 RUONING WANG,2 GERALD FARRELL,3 MENG ZHANG,2 TAO GENG,2 ELFED LEWIS,4 AND KE TIAN2,*

1Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China
2Key Laboratory of In-fiber Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, China
3Photonics Research Centre, Technological University Dublin, Kevin Street, Dublin 8, Ireland
4Optical Fibre Sensors Research Centre, Department of Electronic and Computer Engineering, University of Limerick, Limerick, Ireland
*ketian@hrbeu.edu.cn

Abstract: A temperature-insensitive refractometer based on a refractive index (RI)-modulated singlemode-multimode-singlemode (RMSMS) fibre structure is proposed and experimentally demonstrated. In this investigation, a combination of no-core fibre (NCF) and multimode fibre (MMF) regions provides an RI modulation region due to the difference in RI between the NCF and the MMF. In effect, by periodically embedding the NCF within the MMF section of a singlemode-multimode-singlemode (SMS) fibre structure, a long-period grating (LPG) can be effectively introduced in the MMF section, and the excited cladding modes are therefore able to sense surrounding RI variation. The modulation parameters are determined from the numerical simulations, and the experimental results show the maximum RI sensitivity of the fabricated sample is as high as 206.96 nm/RIU. In addition, the proposed RMSMS fibre structure is proven to be unaffected by external temperature variation (in the wavelength domain), which is a very attractive feature in practical sensing applications.

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1. Introduction

Refractive index (RI) measurement plays a crucial role in environmental monitoring, chemical analysis, medical analysis and biological detection. Among the existing RI sensor technologies, optical fibre based RI sensors have attracted much research attention due to their inherent advantages, such as compact structure, capability of remote monitoring, and immunity to external electromagnetic interference. To date, various optical fibre RI sensors have been successfully proposed, such as based on long-period gratings (LPGs) [1,2], surface plasmon resonance (SPR) [3–6], and different types of fibre optic interferometers, including Mach-Zehnder interferometers (MZIs) [7,8], Fabry-Perot interferometers (FPIs) [9,10], Michelson interferometers [11], and Sagnac interferometers [12]. However, the fabrication cost of these configurations is generally high. For example, the writing of fibre gratings often requires the use of a CO2 laser or an ultraviolet (UV) exposure treatment, SPR based devices typically include a vacuum coating process, and fibre optic interferometers also need high-accuracy fabrication equipment and some expensive specialist fibres such as multi-core fibre, photonic crystal fibre (PCF) and polarization maintaining fibre (PMF). Considering the fabrication cost and the practical applications, the simpler singlemode-multimode-singlemode (SMS) fibre structure has become increasingly popular in recent years.

The multimode interference (MMI) effect, a well-established phenomenon that exists in multimode waveguides, has been intensively investigated. The SMS fibre structure is a very common fibre heterostructure which relies on MMI as its underling operating principle, and
SMS fibre structures have been widely applied in telecommunications [13,14]. In the optical fibre sensing field, SMS fibre structures have also proven to be capable of performing measurements of a wide range of parameters, including temperature [15,16], humidity [17], displacement [18,19], curvature [20], strain [21,22], magnetic field [23] and RI [24–26] etc. A disadvantage of a simple SMS structure is that the cladding layer prevents direct access to the evanescent field by the external environment, thus traditional SMS fibre structures have not been used to directly measure external RI variations. To overcome this, several effective post-processing technologies have been explored, such as tapering [24,25], chemical etching [26], side polishing [17], twisting [20], etc. However some of these approaches often require sophisticated instruments and expensive devices, for example, high-accuracy tapering devices, fibre side-polishing systems or a femtosecond laser, which greatly raises the fabrication cost and limits their applications. In addition, local temperature variations can perturb RI measurement and affect the accuracy of the measurement. The temperature dependence of the traditional SMS fibre structure is about 10 pm/°C [15,20]. To reduce temperature induced cross-sensitivity, some effective methods have been proposed, for example, temperature compensation of SMS fibre structures can be realized by choosing packaging materials with a proper coefficient of thermal expansion (CTE) [27], adjusting the concentration of $P_2O_5$ in the MMF core region [28], or adopting two in-series MMFs with opposite temperature sensitivities [29]. Overall then there is a clear need to find a low-cost method to fabricate an SMS fibre structure that can be used to measure external RI variation, preferably with a very low temperature dependence.

In this article, a temperature-insensitive refractometer based on an RI modulated singlemode-multimode-singlemode (RMSMS) fibre structure is described. The schematic configuration of the proposed RMSMS fibre structure is shown in Fig. 1, in which the sensor structure consists three types of optical fibre, single-mode fibre (SMF), multimode fibre (MMF) and no-core fibre (NCF). By periodically embedding short NCF sections in the MMF section of an SMS fibre structure, the RI of the MMF section is effectively modulated as a function of axial distance due to the RI difference between the NCF and the MMF. Hence, a long-period grating (LPG) is effectively introduced within the MMF section, and the excited cladding modes can be used to sense the surrounding RI variation. Numerical simulations are performed to determine the modulation parameters, and the experimentally fabricated sample show that the maximum RI sensitivity is as high as 206.96 nm/RIU. Additionally, the temperature dependence of the RMSMS is also investigated, and it is demonstrated that the sensor structure is unaffected in wavelength domain by external temperature change which greatly improves its possibility in practical sensing applications.

![Fig. 1. Schematic of the proposed RMSMS fibre structure.](image)

2. Principle and simulation

Figure 2 illustrates the light propagation principle within the RMSMS fibre structure. Before considering a detailed theoretical analysis, an assumption needs to be imposed that all the fibre meridional axes are ideally aligned, so there is no vertical offset at each fibre-fibre interface. As depicted in Fig. 2, the light is initially transmitted along the input SMF core in the fundamental mode ($LP_{01}$). When the light enters the MMF section, a series of high-order
modes are excited. Here, the high-order modes that can be effectively excited are only LP_{0m} modes because of the circular symmetry of the input light field and the above mentioned ideal alignment assumption [30]. The excited mode number $M$ in a step-index MMF can be approximately calculated as follows:

$$M = \frac{d}{\lambda} \sqrt{n_{co}^2 - n_{cl}^2}$$  \hspace{1cm} (1)

where $d$ is the diameter of the MMF core, $n_{co}$ and $n_{cl}$ are the RI of MMF core and cladding, respectively, and $\lambda$ is the free space wavelength. As the light propagates in the MMF section, the electric field distribution $E(r,z)$ at the axial propagation distance $z$ can be expressed as [31]:

$$E(r,z) = \sum_{m=1}^{M} e_m F_m(r) \exp(i\beta_m z)$$  \hspace{1cm} (2)

where $F_m(r)$ is the field profile of LP_{0m}, $\beta_m$ is the propagation constant of the $m$th order mode, and $e_m$ is the corresponding excitation coefficient that can be calculated as follows [32]:

$$e_m = \frac{\int_{0}^{\infty} E(r,0) F_m(r) rdr}{\int_{0}^{\infty} F_m(r) F_m(r) rdr}$$  \hspace{1cm} (3)

As the light propagates in the MMF section, multimode interference (MMI) between the multiple modes occurs. When the light arrives at the RI modulation region, it is coupled between the MMF core and cladding because an LPG is formed in this region due to the periodic RI modulation induced perturbation to the effective RI of the guided modes. Therefore, optical interference also occurs between the forward-propagating core modes and the excited cladding modes. When the phase difference of the $m$th order core mode and $n$th order cladding mode meet the phase matching condition, the corresponding resonance wavelength can be determined as follows [33]:

$$\lambda_{mn} = \left(n_{core}^m - n_{cl}^n\right)\Lambda$$  \hspace{1cm} (4)

where $\Lambda$ is the modulation period. Hence, at the second MMF section, each mode is associated with their respective phase difference and MMI between each mode occurs again. Ultimately, when the light arrives at the output MMF/SMF interface, a portion of the light is coupled into the core of the output SMF which can be detected by an appropriate interrogation system. The remaining light is coupled into the cladding due to the mode field mismatch, and is leaked out of the fibre over a short propagation distance. When the external RI is changed, the effective RI of the cladding modes is varied which in turn results in a variation of the interference conditions and finally change the transmission spectrum.

In order to describe the optical field distribution within the RMSMS fibre structure and determine the modulation parameters, numerical simulations using the Beam Propagation
Method (BPM) have been carried out. Besides this essential RMSMS fibre model, a traditional SMS fibre model was also developed for comparison. In the simulation, the numerical mesh size in the profile directions X, Y, and propagation direction Z were set as 0.1 \( \mu \text{m} \), 0.1 \( \mu \text{m} \) and 1 \( \mu \text{m} \), respectively. The specific geometry/RI parameters of SMF, MMF, and NCF that were used were: the core/ cladding diameters and RI for the SMF and MMF are 8.3/125 \( \mu \text{m} \) and 1.4504/1.4447; 105/125 \( \mu \text{m} \) and 1.4446/1.4271, respectively, the diameter of the NCF is 125 \( \mu \text{m} \) and its RI is 1.444. In this case, the overall length of MMF was chosen to be 2 cm because it provides a quasi-image distance at start of the modulation region [34], making the coupling of the light between the core and the cladding more efficient. The modulation period \( \Lambda \) was chosen to be 600 \( \mu \text{m} \) which consists of a 200 \( \mu \text{m} \) length NCF and 400 \( \mu \text{m} \) length MMF, as it represents a typical grating period length for a long-period grating [35], and more importantly, practical fabrication such as fibre cutting is relatively straightforward for these section lengths. The length of the RI modulation region was finally designed to be 3.8 mm, and this was based on the simulation results below that when the number of embedded NCF sections reached 7, the light in the MMF core could be most effectively coupled into the cladding. Moreover, at this value, the resulting transmission spectrum also exhibits good contrast.

The simulation results are shown in Fig. 3, for a free space wavelength set to 1550 nm. Figure 3(a) shows the optical field intensity distribution within a traditional SMS fibre structure. It can be seen that multiple modes are excited when the light is launched from the SMF into the MMF interface, and the expected MMI pattern appears within the MMF section. Most importantly in Fig. 3(a), it is clear that all modes are confined to the MMF core, again as expected, and no light enters into the MMF cladding. Figure 3(b) shows the optical field distribution within a RMSMS fibre structure. It is clear that when the light transmits the RI modulation region, cladding modes are excited in the MMF cladding, which in turn plays a vital role in RI measurement.

Fig. 3. Simulated optical field intensity distribution (a) within a traditional SMS fibre structure; (b) within a RMSMS fibre structure.

The corresponding transmission spectra of the traditional SMS fibre structure and the RMSMS fibre structure were simulated and are shown in Fig. 4(a). For a traditional SMS
fibre structure using a 2 cm long MMF, no discernable interference pattern appears over the wavelength range of 1500 nm to 1600 nm. However, in the RMSMS case given the RI modulation, the interference pattern is enhanced and there a clear interference dip appears at 1521 nm with a good extinction ratio (more than 10 dB). The surrounding RI is set as 1.333 for this simulation.

The spectral response characteristics of the RMSMS fibre structure as the surrounding RI is changed was also examined in simulation, assuming the background refractive index was changed from 1.333 RIU to 1.405 RIU, and the results are shown in Fig. 4(b). From Fig. 4(b), it can be seen that the monitored dip exhibits a clear red shift in wavelength domain and accompanied by an intensity increase (a decrease in the depth of the dip) as the external RI is increased. The calculated wavelength shift of the dip was plotted and characterized using a polynomial fit against the RI value in Fig. 4(c). It can be seen that the fitting curve exhibits a high correlation factor of 0.9989, and the maximum RI sensitivity was calculated to be 707.46 nm/RIU. In summary, simulations have shown that the RMSMS fibre structure in this investigation is proven to be feasible as an RI sensor. The modulation parameters simulated were also used as the basis for the experimental sample fabrication process which follows.

3. Device fabrication

The cut lengths of the NCF and MMF sections are a key parameter in the fabrication of the RMSMS. For this reason, a precise cutting system was employed which is illustrated in Fig. 5(a). The system comprises three 3-axis translation stages, one fibre cleaver, one CCD and one PC. The left and right translation stages were used to fix the optical fibre to the same horizontal axes, and the middle translation stage was connected to a fibre cleaver and was
used to manually and precisely adjust the location of the fibre cleaver relative to the optical fibre. The CCD and the PC were used to monitor the distance between the splicing point and the cutting profile to ensure the accuracy of the cutting length.

![Diagram](image1)

Fig. 5. (a) Schematic diagram of the fibre micro-cutting system; (b1-b3) Schematic diagram of the fabrication process for the RMSMS fibre structure.

The fabrication process for the RMSMS fibre structure is relatively simple as only fibre splicing and cleaving steps are involved. Figure 5(b1-b3) depicts the specific fabrication processes. Initially, a single-mode fibre (SMF-28, Corning) was fusion spliced to a 1 cm length of MMF (AFS 105/125, Thorlabs). The other end of the MMF was then spliced to a section of NCF, and the length of NCF was then cleaved to a length of 200 μm. Next, the 200 μm length NCF was spliced to a 400 μm length of MMF to form a fibre combination with an overall length of 600 μm with RI modulation. The above steps of b2 and b3 were repeated 7 and 6 times, respectively, to create a periodic RI modulation region. Following completion of the fabrication of the RI modulation region, the free end of the NCF was finally spliced to an MMF/SMF structure (where the length of the MMF is 1 cm) to complete the RMSMS fibre structure.

Figure 6(a) is a microscope image of the fabricated RMSMS fibre sample. The length of the NCF and MMF in the modulation region was measured using a high-precision optical microscope (Nikon, LV100N), and the specific length values are shown in Table 1. From Table 1, it can be seen that all the fibres (NCF and MMF) were accurately cut by the cutting system and the cutting length error is less than 2 μm. The transmission spectrum of the RMSMS fibre sample was measured and is shown in Fig. 6(b). Here, the RMSMS fibre sample was immersed in deionized water to provide a surrounding RI value of 1.333, in line with the assumed value used in the simulation for the sake of consistency. From Fig. 6(b), it can be seen that the measured results agree well with the simulation results, and the experimentally obtained interference dip is located at a wavelength of 1523.2 nm.
Fig. 6. (a) Microscope images of the fabricated RMSMS fibre sample; (b) Simulated and experimental transmission spectra of the RMSMS fibre structure (in water).

Table 1. Measurement lengths of the embedded NCF and MMF

<table>
<thead>
<tr>
<th>Fibre number</th>
<th>Length of NCF (μm)</th>
<th>Length of MMF (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200.34</td>
<td>399.08</td>
</tr>
<tr>
<td>2</td>
<td>201.58</td>
<td>398.85</td>
</tr>
<tr>
<td>3</td>
<td>199.89</td>
<td>401.02</td>
</tr>
<tr>
<td>4</td>
<td>200.62</td>
<td>400.33</td>
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<tr>
<td>5</td>
<td>201.61</td>
<td>401.05</td>
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<tr>
<td>6</td>
<td>200.53</td>
<td>400.81</td>
</tr>
<tr>
<td>7</td>
<td>199.64</td>
<td>-</td>
</tr>
</tbody>
</table>

4. Experiment and discussion

The experimental setup for RI measurement is depicted in Fig. 7. The RMSMS fibre sample was placed on a PolyMethyl Methacrylate (PMMA) polymer substrate and fixed using ultraviolet (UV) glue to enhance its stability. A simple polymer wall was wrapped around the edge of the plate in order to prevent RI solution leakage. In this experiment, glycerin was used to create the RI solution, and different RI solutions can be obtained by controlling the concentration of glycerin in deionized water. Prior to each RI measurement, the fibre sample was thoroughly cleaned using deionized water and alcohol, the aim being to eliminate any cross-contamination between the different RI value solutions to ensure the efficacy of the experimental results. A supercontinuum light source (SCS, YSL, China) was used to provide input broadband light, and the output transmission spectrum signal was monitored using a high-resolution (20 pm) optical spectrum analyzer (OSA, YOKOGAWA AQ6370D, Japan).

Figure 8(a) shows the spectral evolution results as the external RI was changed from 1.333 RIU to 1.405 RIU. As shown in Fig. 8(a), when the external RI was increased, the monitored dip exhibits a clear red-shift in the wavelength domain which was also accompanied by an intensity increase. This observed dip evolution trend is consistent with the
simulated results which were presented in Fig. 4(b). The resulting wavelength shift of the dip was plotted and characterized using a polynomial fit against the RI value in Fig. 8(b). It can be seen that the fitting curve exhibits a high correlation factor of 0.9979, and the maximum RI sensitivity was calculated to be 206.96 nm/RIU. Given the 0.02 nm spectral resolution of the OSA used in the experiment, the RI measurement resolution achieved by this RI sensor of this investigation was calculated to be $9.7 \times 10^{-5}$ RIU. The RI sensitivity achieved in the experiment is lower than the maximum sensitivity determined from the simulation. This disparity could be attributed to the length errors for the various fibre sections in the RI modulated region and the non-ideal alignments between the SMF, MMF, and NCF. Also, there are some approximations in the BPM simulation module, for example only LP$_{0m}$ modes are considered in the theoretical calculation.

Fig. 8. (a) Transmission spectrum evolution as external RI is changed; (b) Fitting curve of the dip wavelength shift against RI variation.

In addition to the fundamental RI measurement, the temperature response characteristics of the proposed RMSMS fibre structure were also investigated. In this test, the sample was placed inside a climate chamber (ESPEC SH-222, Japan), in which the temperature was accurately controlled. The temperature of the chamber was changed from 10 °C to 45 °C with a step of 5 °C, and the corresponding spectral evolution results are shown in Fig. 9. From Fig. 9(a), it can be observed that the dip exhibits no significant shift in wavelength domain, and is accompanied by a very small dip intensity variation. Figure 9(b) includes a graph of the experimental temperature dependence of the wavelength and intensity values recorded at the dip minimum and this clearly shows that the dip wavelength remains unchanged at 1519.7 nm whilst the observed dip intensity variation was only 0.4884 dB as the temperature was changed from 10 °C to 45 °C. This is a very attractive feature for an optical fibre RI sensor, as it means that the RI sensor wavelength response is unaffected by temperature and does not require additional temperature compensation. It is worth noting that temperature variation also results in a change in RI value of the liquid under test [36,37], therefore in practical RI measurement, the thermo-optical coefficient (TOC) of the tested liquid should be known, and hence a simple spectral calibration can be implemented to ensure the accuracy of the measurement.
Table 2 gives a direct comparison of the RI sensing performance between the RI modulated SMS fibre structure proposed in this investigation and the other measurement configurations cited in this article. From Table 2, it can be seen that the developed sensor in this investigation provides a common RI sensitivity when compared to the previous reported scenarios. However, the greatest strength of the proposed RI modulated SMS fibre structure is that there is no temperature-RI crosstalk. In addition, the fabrication cost of the RI modulated SMS fibre structure is low, and its fabrication process is relatively simple and straightforward. Therefore, the developed RI modulated SMS fibre sensor in this investigation can be a competitive candidate for use in practical RI sensing applications.

Table 2. Comparison of the sensing performance of different RI sensors developed to date

<table>
<thead>
<tr>
<th>Measurement configuration</th>
<th>RI sensitivity (nm/RIU)</th>
<th>Measurement range</th>
<th>Temperature-RI crosstalk (RIU/°C)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>1300</td>
<td>1.404-1.452</td>
<td>3.54 × 10^{-5}</td>
<td>1</td>
</tr>
<tr>
<td>Zinc oxide coated LPG</td>
<td>806</td>
<td>1.320-1.360</td>
<td>Not given</td>
<td>2</td>
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<tr>
<td>SPR based on tapered coreless fibre</td>
<td>2278.4</td>
<td>1.330-1.391</td>
<td>Not given</td>
<td>3</td>
</tr>
<tr>
<td>SPR incorporating dielectric layer</td>
<td>5199.4</td>
<td>1.333-1.353</td>
<td>Not given</td>
<td>4</td>
</tr>
<tr>
<td>SPR based on multi-tapered fibre</td>
<td>2250-3500</td>
<td>1.330-1.380</td>
<td>Not given</td>
<td>5</td>
</tr>
<tr>
<td>SPR incorporating oxide layer</td>
<td>2750-3250</td>
<td>1.330-1.370</td>
<td>Not given</td>
<td>6</td>
</tr>
<tr>
<td>MZI based on dual-core fibre</td>
<td>294.5</td>
<td>1.335-1.395</td>
<td>Not given</td>
<td>7</td>
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<tr>
<td>MZI based on tapered SMF</td>
<td>–26.087</td>
<td>1.333-1.363</td>
<td>2.95 × 10^{-3}</td>
<td>8</td>
</tr>
<tr>
<td>FPI based on micro-notch cavity</td>
<td>1163</td>
<td>Around 1.333</td>
<td>1.1 × 10^{-6}</td>
<td>9</td>
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<tr>
<td>FPI based on micro-air cavity</td>
<td>1130.887</td>
<td>1.333-1.395</td>
<td>7 × 10^{-7}</td>
<td>10</td>
</tr>
<tr>
<td>Michelson interferometer</td>
<td>270</td>
<td>1.333-1.3776</td>
<td>7.04 × 10^{-4}</td>
<td>11</td>
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<td>Sagnac interferometer</td>
<td>–3137</td>
<td>1.332-1.345</td>
<td>Not given</td>
<td>12</td>
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<td>Single-tapered SMS fibre structure</td>
<td>1900</td>
<td>1.330-1.440</td>
<td>Not given</td>
<td>24</td>
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<td>Multi-tapered SMS fibre structure</td>
<td>261.9</td>
<td>1.3333-1.3737</td>
<td>Not given</td>
<td>25</td>
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<td>Chemical etched SMS fibre structure</td>
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<td>1.342-1.437</td>
<td>Not given</td>
<td>26</td>
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<tr>
<td>LPG</td>
<td>141.837</td>
<td>1.333-1.400</td>
<td>4.53 × 10^{-5}</td>
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<td>RI modulated SMS fibre structure</td>
<td>206.96</td>
<td>1.333-1.405</td>
<td>0</td>
<td>This work</td>
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</table>

5. Conclusion

In this article, a temperature-insensitive refractometer based on a refractive index (RI) modulated singlemode-multimode-singlemode (RMSMS) fibre structure has been presented and experimentally demonstrated. By periodically embedding sections of NCF within the MMF section of an SMS fibre structure, the RI of the MMF section was successfully
modulated and the cladding modes were effectively excited within the MMF section. Therefore, the surrounding RI variation was accurately measured using this RMSMS fibre structure. An experimental sample was fabricated based on the simulation determined fabrication parameters, and a maximum RI sensitivity 206.96 nm/RIU has been achieved experimentally. In addition, the proposed fibre structure was proven to be unaffected by external temperature variation, which is a highly attractive feature for use in a wide range of practical applications. The proposed fibre RI sensor of this investigation is therefore a realistic candidate to be applied in biosensing as well as other RI measurement fields, e.g. chemical processing, oil and gas exploration etc.

**Funding**

National Key R&D Program of China (2016YFE0126500); National Natural Science Foundation of China (NSFC) (61575050); Fundamental Research Funds for the Central Universities (HEUCFG201841); Key Program for Natural Science Foundation of Heilongjiang Province of China (ZD2016012); Open Fund of the State Key Laboratory on Integrated Optoelectronics (IOSKL2016KF03); 111 project (B13015) to the Harbin Engineering University; Ph. D Student Research and Innovation Fund of the Fundamental Research Funds for the Central Universities (HEUGIP201820).

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