Photonic Sensors ([illegible]) [illegible]

[illegible] **Photonic Sensors**

Review

Tilted Fiber Bragg Gratings: Principle and Sensing Applications

[illegible]

[illegible]*Key Laboratory of Opto-Electronic Information and Technology, Ministry of Education, Institute of Modern Optics, Nankai University, Tianjin, 300071, China*

[illegible]*Tianjin Key Laboratory of Film Electronic and Communication Device, School of Electronics Information Engineering, Tianjin University of Technology, Tianjin, 300384, China*

*[illegible]

Abstract: [illegible] ([illegible]) [illegible] ([illegible]) [illegible]

Keywords: [illegible] ([illegible]) [illegible]

1. Introduction

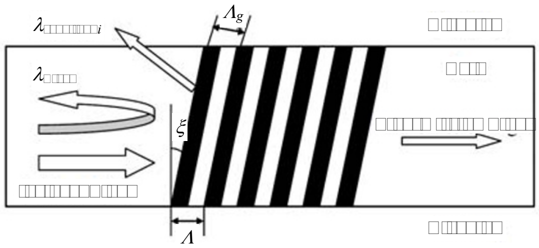
[illegible] ([illegible]) [illegible] *et al* [illegible]

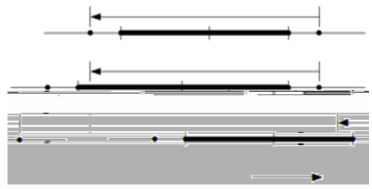
[illegible] *et al* [illegible] ([illegible]) [illegible] ([illegible]) [illegible] ([illegible]) [illegible]

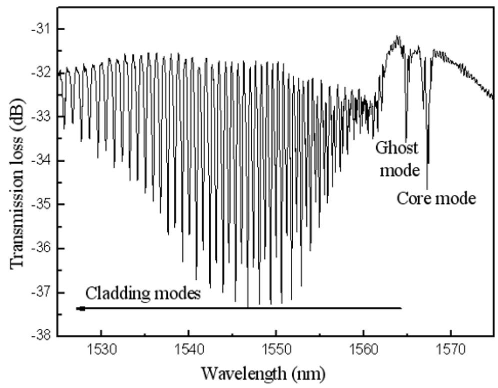
[illegible]

[illegible] ([illegible]) [illegible]

2. Mode coupling mechanism in TFBGs







$$\lambda = (n + n)\Lambda_g$$ (□)

n … Λ_g …

$$\Lambda_g = \frac{\Lambda}{\xi}$$ (□)

(□) (□)

$$\lambda = (n + n)\frac{\Lambda_g}{\xi}$$ (□)

$$\lambda_{i} = (n + n_{i})\frac{\Lambda_g}{\xi}$$ (□)

n_{i} … i

3. Development of TFBG fabrication technique

et al … (□□□) … (□□) … *et al* … *et al* [illegible] et al [illegible]

4. Theoretical progress of TFBG research

[illegible]

[illegible] ([illegible]) [illegible]

[illegible] et al [illegible]

[illegible] et al. [illegible] et al [illegible] et al. [illegible] et al [illegible]

5. Sensing applications of TFBG research

[illegible]

[illegible] ([illegible]) [illegible] & [illegible] ([illegible]) [illegible]

[illegible]

5.1 Basic sensing applications of TFBG sensors

5.2 Refractometer and concentration sensors

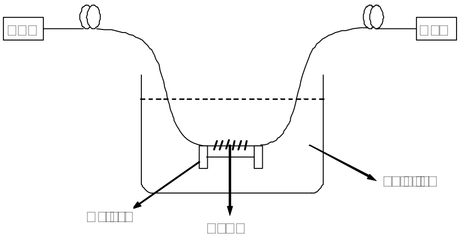
5.3 All fiber interrogation technique of TFBG sensors

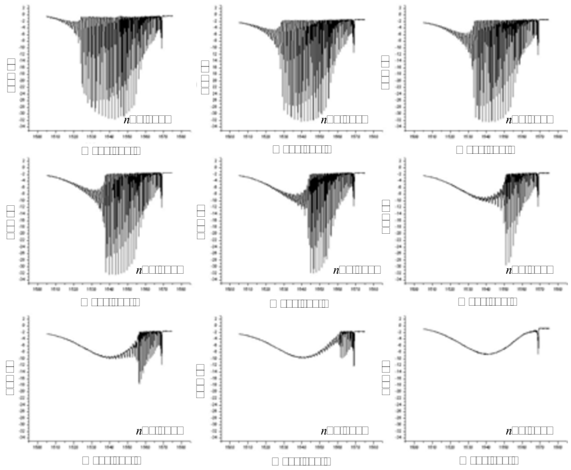
5.4 Extended applications of TFBG sensors using new materials

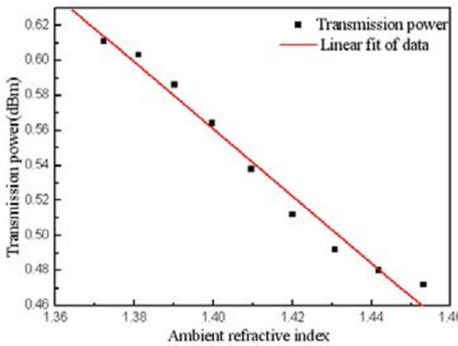
6. Current research activities on TFBG sensors at IMONK

6.1 TFBG sensors for single-parameter measurement

6.1.1 TFBG sensor for refractive index measurement [58]



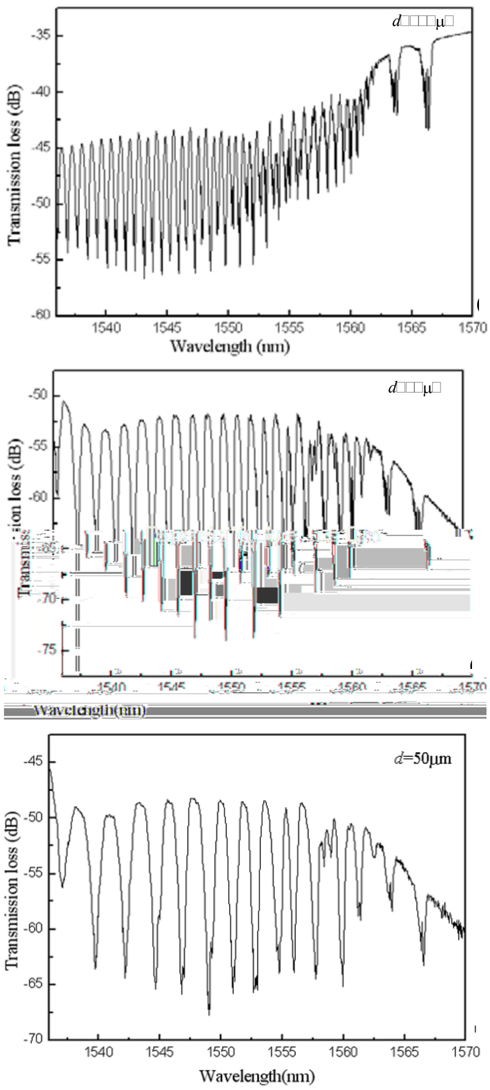


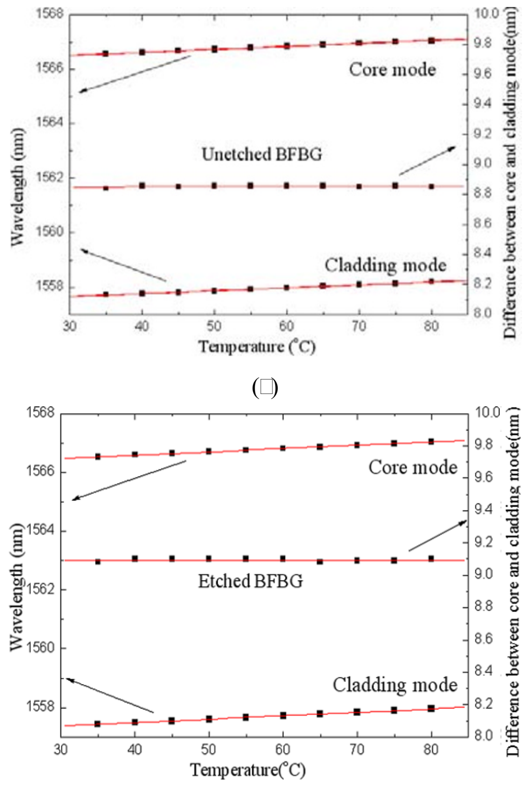


6.1.2 HF-etched TFBG refractometer with enhanced sensitivity [59]

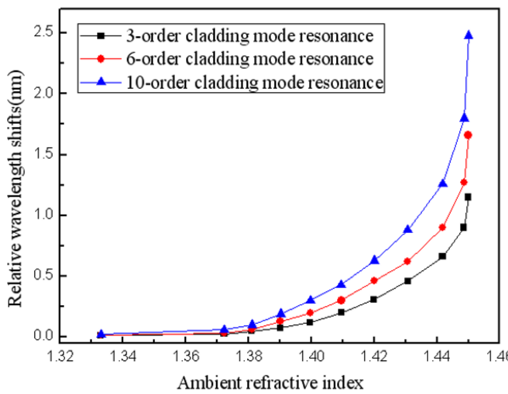
( )

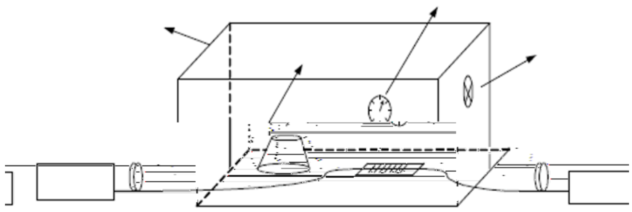
μ μ μ

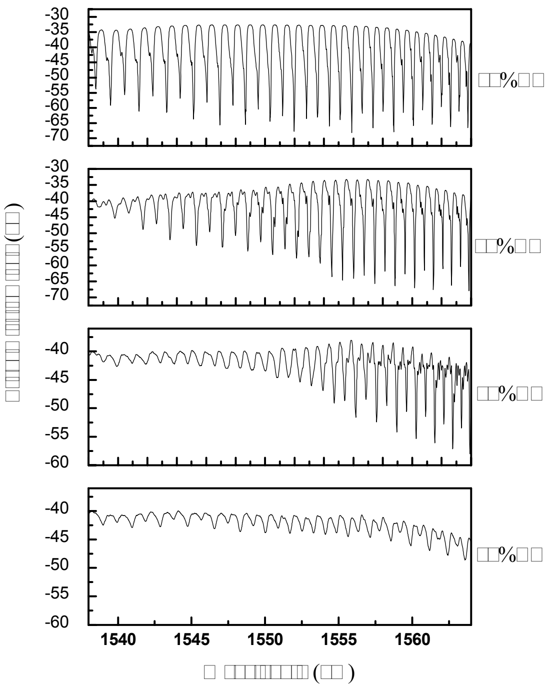

Transmission loss (dB)
Wavelength (nm)
d=50μm
Wavelength(nm)


Wavelength (nm)
Difference between core and cladding mode(nm)
Core mode
Unetched BFBG
Cladding mode
Temperature (°C)
Etched BFBG
Temperature(°C)

6.1.3 TFBG sensor for relative humidity measurement [60]

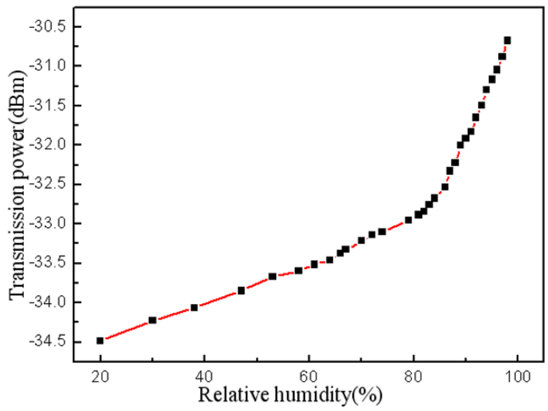





1540
1545
1550
1555
1560

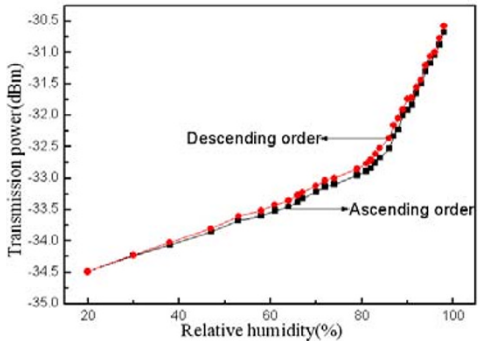
[illegible]

[illegible]


Transmission power(dBm)
Relative humidity(%)

[illegible]

[illegible]



[illegible] % [illegible] – [illegible] % [illegible]

6.1.4 Bending and directional characteristics of TFBG [61]

[illegible]

$$N^{[illegible]}_{[illegible]}(x) = n^{[illegible]}_{[illegible]}(x) + \frac{[illegible]}{[illegible]k^{[illegible]}_{[illegible]}R^{[illegible]}} + \frac{[illegible]}{R}\left(n^{[illegible]}_{[illegible]} - \frac{[illegible]}{[illegible]k^{[illegible]}_{[illegible]}R^{[illegible]}}\right)x \quad ([illegible])$$

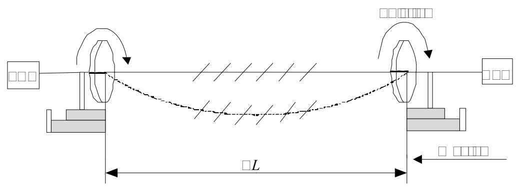
[illegible] $k_{[illegible]} = [illegible]\pi [illegible]\lambda$ [illegible] R [illegible] $n_{[illegible]}(x)$ [illegible] $n_{[illegible]}$ [illegible] x [illegible]

[illegible]

[illegible] ([illegible] μ[illegible] μ[illegible]) [illegible]

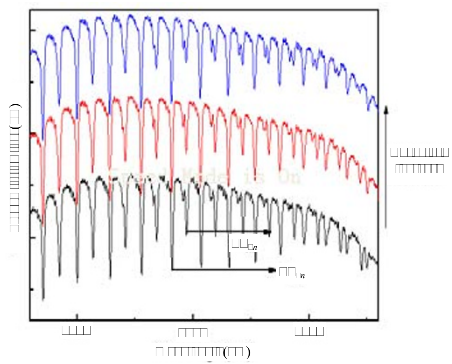
$$C = \frac{[illegible]d}{d^{[illegible]} + L^{[illegible]}} \quad ([illegible])$$

[illegible] d [illegible] L [illegible]



[illegible]

[illegible] – [illegible] $^{-[illegible]}$ [illegible] $_n$ [illegible] $_n$ [illegible]



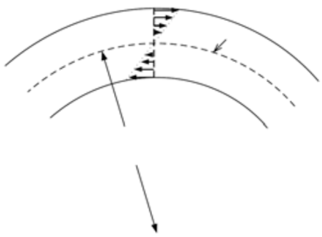
[illegible]

(ε)

x

R

$$\varepsilon = \frac{x}{R}$$



x

y

$$\Delta n_{st} = -(n)\left[(\,-\nu)\,p - \nu\, p\right]\overline{R}$$

ν

p_{ij}

n

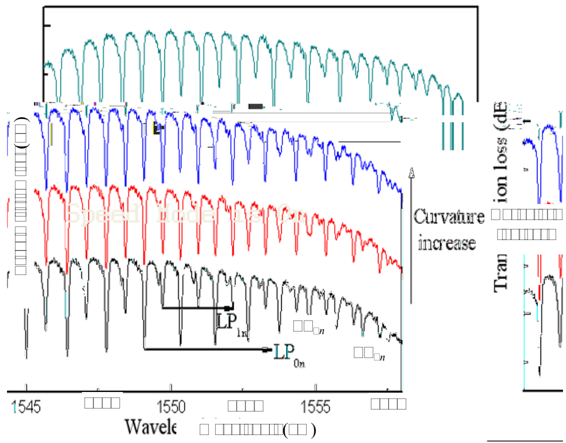
$$\Delta\lambda = (\,-p_e)\frac{D}{R}$$

$p_e =$

D

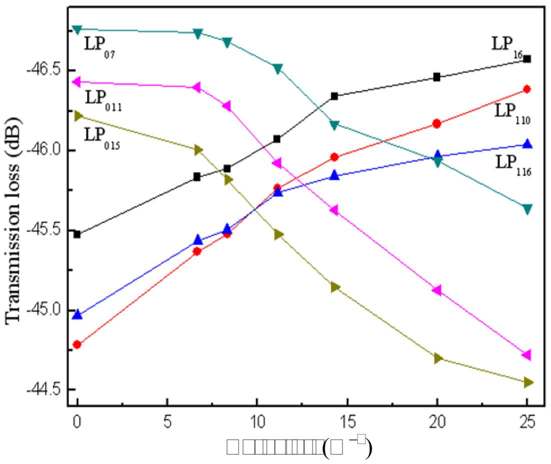
$$\kappa_{\nu-}(z) = \frac{w\varepsilon\, n\, \sigma(z)}{} \int^{\pi} d\phi \int^{a} r dr (E_r E_r^{*} + E_\phi E_\phi^{*})$$

$E(r\phi)$ $E(r\phi)$



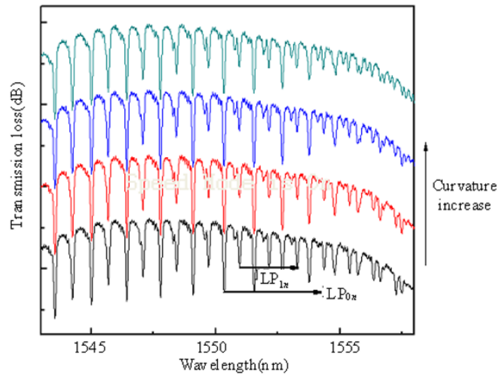
[illegible]

[illegible]



[illegible]

[illegible]



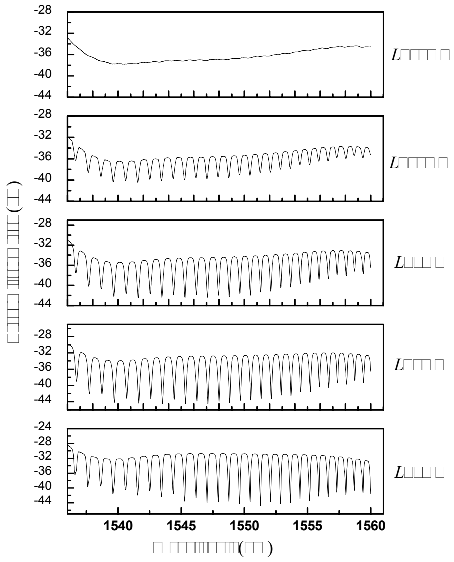
[illegible]

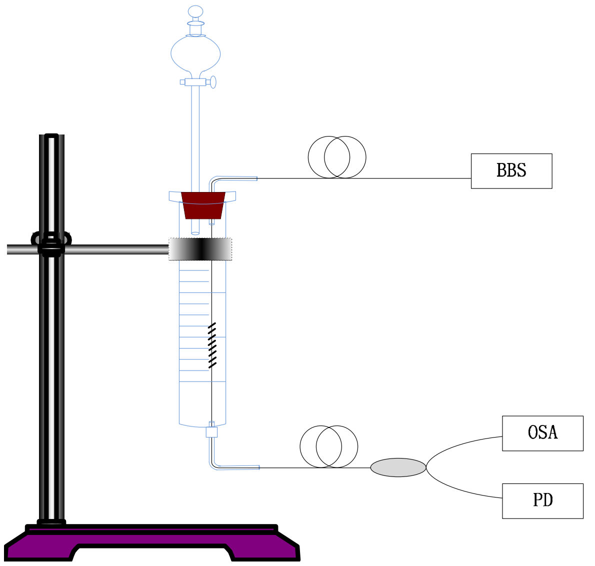
[illegible]

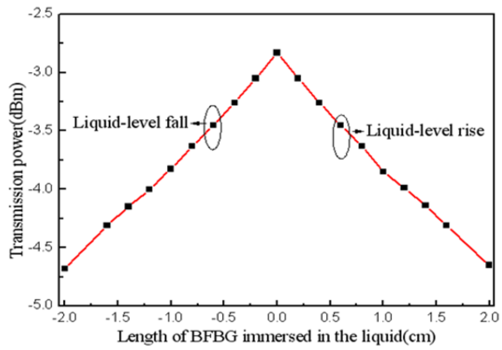
6.1.5 TFBG sensor for liquid-level measurement [66]

[illegible]

[illegible]


1540
1545
1550
1555
1560


BBS
OSA
PD


Transmission power(dBm)
Liquid-level fall
Liquid-level rise
Length of BFBG immersed in the liquid(cm)

[illegible]

6.2 Temperature cross sensitivity of TFBG sensors

[illegible]

6.2.1 TFBG sensor for simultaneous measurement of strain and temperature [67]

[illegible]

$$\frac{\Delta\lambda_B}{\lambda_B}=\left(\frac{[illegible]}{n_{[illegible]}}\frac{\partial n_{[illegible]}}{\partial T}+\frac{[illegible]}{\Lambda_g}\frac{\partial\Lambda_g}{\partial T}\right)\Delta T+\left(\frac{[illegible]}{\Lambda_g}\frac{\partial\Lambda_g}{\partial\varepsilon}+\frac{[illegible]}{n_{[illegible]}}\frac{\partial n_{[illegible]}}{\partial\varepsilon}\right)\Delta\varepsilon=K_{[illegible]T}\Delta T+K_{[illegible]\varepsilon}\Delta\varepsilon$$

$$\frac{\Delta\lambda^i_{[illegible]}}{\lambda^i_{[illegible]}}=\left\{\frac{[illegible]}{n^i_{[illegible]}+n^i_{[illegible]}}\frac{\partial(n^i_{[illegible]}+n^i_{[illegible]})}{\partial T}+\frac{[illegible]}{\Lambda_g}\frac{\partial\Lambda_g}{\partial T}\right\}\Delta T+\left\{\frac{[illegible]}{\Lambda_g}\frac{\partial\Lambda_g}{\partial\varepsilon}+\frac{[illegible]}{n^i_{[illegible]}+n^i_{[illegible]}}\frac{\partial(n^i_{[illegible]}+n^i_{[illegible]})}{\partial\varepsilon}\right\}\Delta\varepsilon=K_{[illegible]T}\Delta T+K_{[illegible]\varepsilon}\Delta\varepsilon$$

[illegible] $K_{[illegible]T}$ [illegible] $K_{[illegible]T}$ [illegible] $K_{[illegible]\varepsilon}$ [illegible] $K_{[illegible]\varepsilon}$ [illegible]

$$\begin{pmatrix}\Delta\lambda_{[illegible]}\\ \Delta\lambda_{[illegible]}\end{pmatrix}=\begin{pmatrix}K_{[illegible]T} & K_{[illegible]\varepsilon}\\ K_{[illegible]T} & K_{[illegible]\varepsilon}\end{pmatrix}\begin{pmatrix}\Delta T\\ \Delta\varepsilon\end{pmatrix}$$

[illegible] $\Delta\lambda_{[illegible]}$ [illegible] $\Delta\lambda_{[illegible]}$ [illegible] $\Delta\varepsilon$ [illegible] ΔT [illegible] $K_{[illegible]T}$, $K_{[illegible]T}$, $K_{[illegible]\varepsilon}$, [illegible] $K_{[illegible]\varepsilon}$ [illegible]

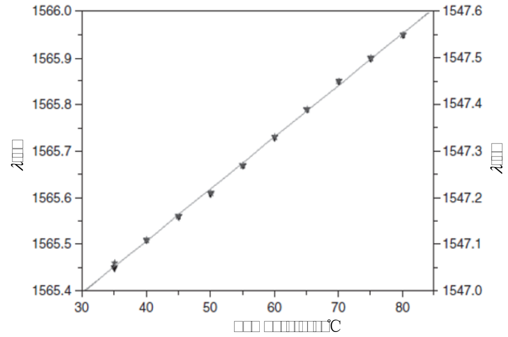
$$\begin{pmatrix}\Delta T\\ \Delta\varepsilon\end{pmatrix}=\begin{pmatrix}K_{[illegible]T} & K_{[illegible]\varepsilon}\\ K_{[illegible]T} & K_{[illegible]\varepsilon}\end{pmatrix}^{-[illegible]}\begin{pmatrix}\Delta\lambda_{[illegible]}\\ \Delta\lambda_{[illegible]}\end{pmatrix}$$

[illegible] ℃ [illegible]

[illegible] ℃ [illegible]

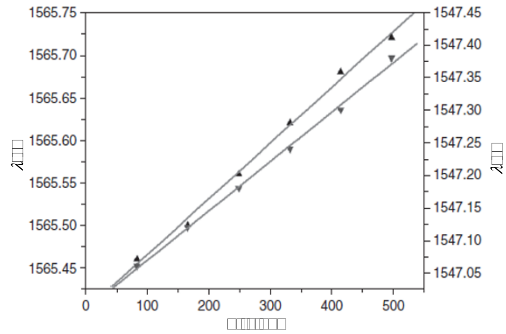
[illegible]

[illegible]



[illegible]

[illegible] K_{T}, K_{ε}, K_{T} [illegible] K_{ε} [illegible] ℃ [illegible] με [illegible] ℃ [illegible] με [illegible] [illegible] ([illegible])

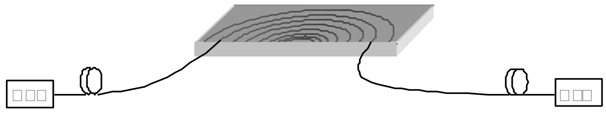


[illegible]

6.2.2 TFBG sensor for simultaneous discrimination of bending and temperature [68]

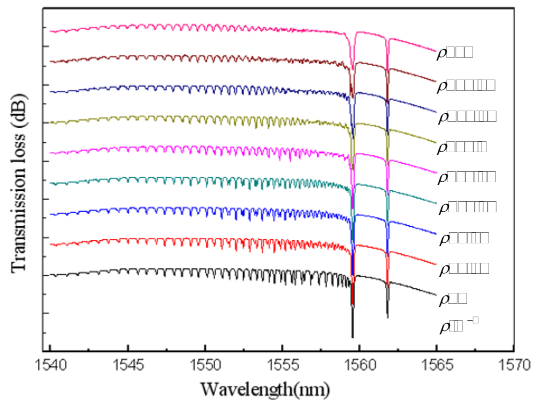
[illegible]

[illegible]



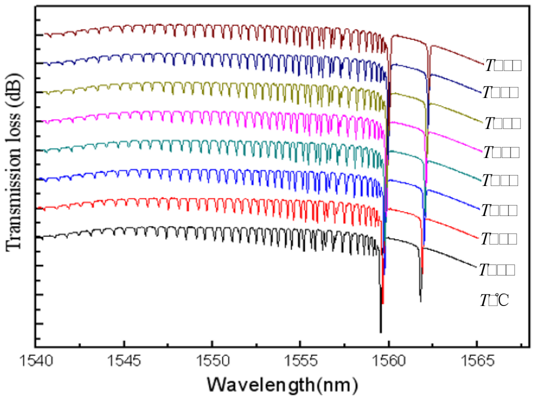
[illegible]

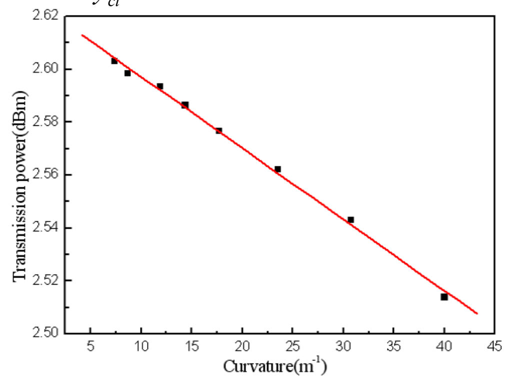
[illegible]

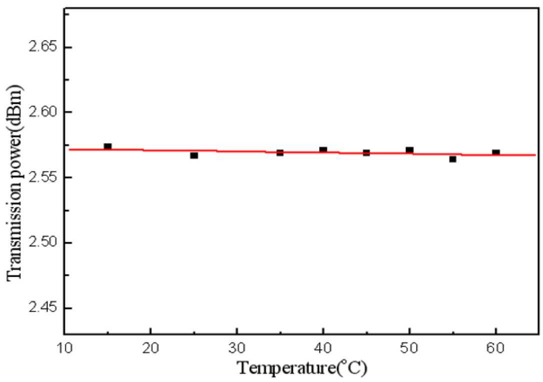


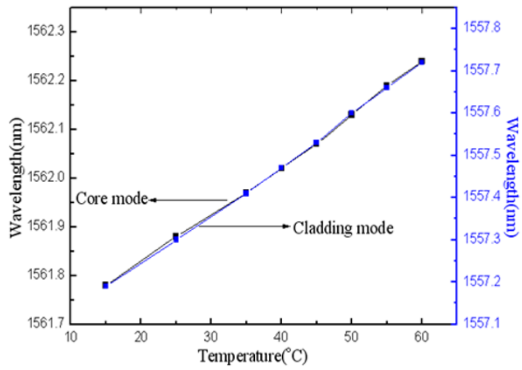
[illegible]

[illegible]


Transmission loss (dB)
Wavelength(nm)
1540
1545
1550
1555
1560
1565
℃

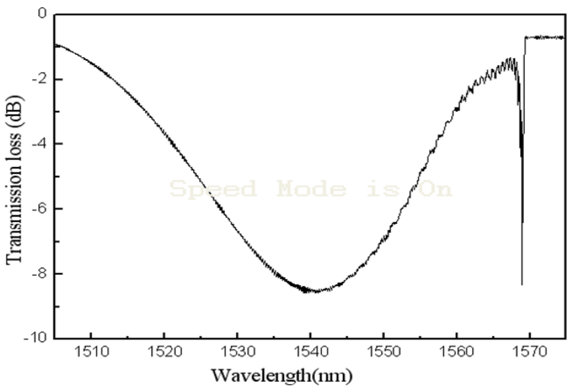

Transmission power(dBm)
Curvature(m-1)
2.62
2.60
2.58
2.56
2.54
2.52
2.50
5
10
15
20
25
30
35
40
45

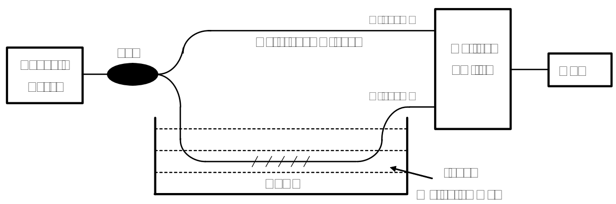

Transmission power(dBm)
Temperature(°C)
2.65
2.60
2.55
2.50
2.45
10
20
30
40
50
60


Wavelength(nm)
Wavelength(nm)
Temperature(°C)
Core mode
Cladding mode
1562.3
1562.2
1562.1
1562.0
1561.9
1561.8
1561.7
1557.8
1557.7
1557.6
1557.5
1557.4
1557.3
1557.2
1557.1
10
20
30
40
50
60

6.3 TFBG-based interrogation technique

6.3.1 TFBG-based edge filtering interrogation technique [69]



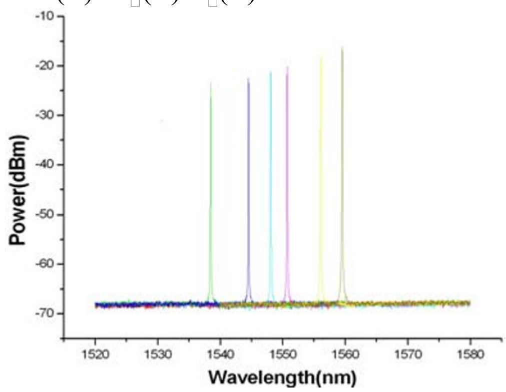


$$H(\lambda) = I_{[illegible]}(\lambda) \, [illegible] \, I_{[illegible]}(\lambda) \quad ([illegible])$$

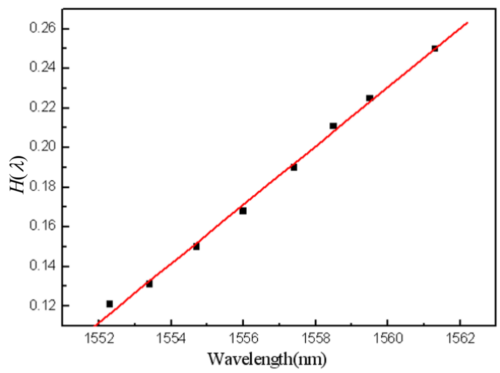
[illegible]

$H(\lambda)$ [illegible]

$H(\lambda)$ [illegible] $I(\lambda)$ [illegible] $I(\lambda) =$ [illegible] $\lambda -$ [illegible]



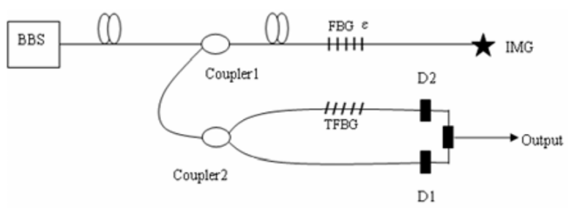
[illegible]



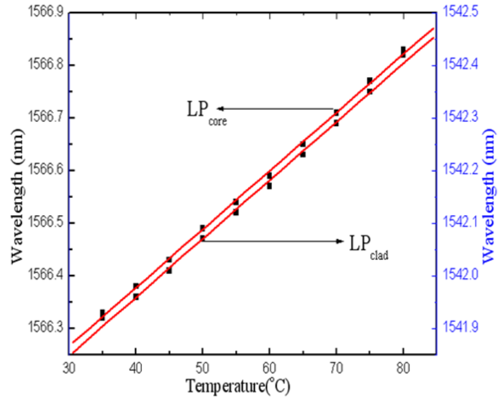
[illegible]

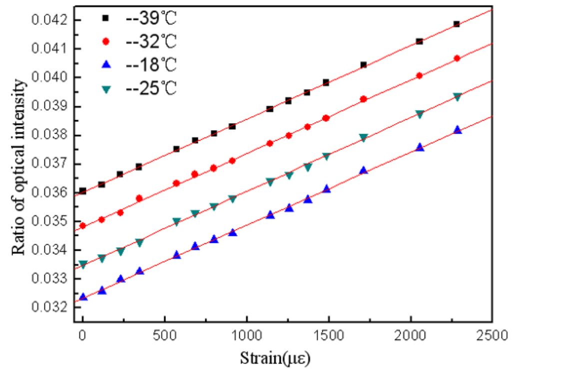
6.3.2 TFBG-based dynamic temperature compensation interrogation technique for strain sensors [70]

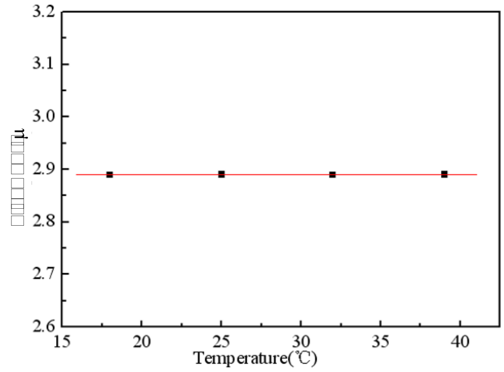
[illegible]



[illegible]







7. Brief summary on the key techniques of TFBG sensors

8. Prospects of research and applications of TFBGs

9. Conclusions

[illegible]

Acknowledgment

[illegible]

References

1. [illegible] *Appl. Phys. Lett.* [illegible]
2. [illegible] *Appl. Opt.* [illegible]
3. [illegible] *Opt. Fiber Technol.* [illegible]
4. [illegible] *Sens. Actuators A: Phys.* [illegible]
5. [illegible] *IEEE Sens. J* [illegible]
6. [illegible] *Chin. Phys. Lett.* [illegible]
7. [illegible] *Optical fiber Communication Conference, OFC'90* [illegible]
8. [illegible] *Opt. Express* [illegible]
9. [illegible] *Electron. Lett.* [illegible]
10. [illegible]° [illegible] *Electron. Lett.* [illegible]
11. [illegible] *IEEE Photon. Technol. Lett.* [illegible]
12. [illegible] *J. Opt. Soc. Am. A* [illegible]
13. [illegible] *Appl. Opt.* [illegible]
14. [illegible] *J. Opt. Soc. Am. A* [illegible]
15. [illegible] *IEEE Photon. Technol. Lett.* [illegible]
16. [illegible] *Opt. Lett.* [illegible]

[illegible] *IEEE J. Lightwave Technol.* [illegible]

[illegible] *J. Opt. Soc. Am. B* [illegible]

[illegible] *Microw. Opt. Technol Lett.* [illegible]

[illegible] *J. Opt. Soc. Am. B* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *Opt. Express* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Meas. Sci. Technol.* [illegible]

[illegible] *Opt. Commun.* [illegible]

[illegible] *Optical Fiber Communication Conference* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] ° [illegible] *Opt. Lett.* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Meas. Sci. Technol.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Optical Sensors 2008* [illegible]

[illegible] *Meas. Sci. Technol.* [illegible]

[illegible] *Opt. Lett.* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *Appl. Opt.* [illegible]

[illegible]

[illegible] *17th International Conference on Optical Fibre Sensors* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible]° [illegible] *IEEE J. Lightwave Technol.* [illegible]

[illegible]° [illegible] *Opt. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Opt. Express* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Opt. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *Opt. Lett.* [illegible]

[illegible] *Opt. Express* [illegible]

[illegible] *Optical Fiber Sensors* [illegible]

[illegible] *Opt. Express* [illegible]

[illegible] *Opt. Lett.* [illegible]

[illegible] *J. Opt. Soc. Am. B* [illegible]

[illegible] *Opt. Fiber Technol.* [illegible]

[illegible] *Microw. Opt. Technol. Lett.* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]

[illegible] *20th International Conference on Optical Fibre Sensors* [illegible]

[illegible] *Fiber Optic Sensor Technology and Applications IV* [illegible]

[illegible] *J. Lightwave. Technol. Lett.* [illegible]

[illegible] *J. Lightwave Technol.* [illegible]

[illegible] *J. Lightwave Technol.* [illegible]

[illegible] *2010 3rd Asia-Pacific Optical Fiber Sensors Conference* [illegible]

[illegible] *Electron. Lett.* [illegible]

[illegible] *Chin. J. Lasers* [illegible] ([illegible])

[illegible] *Proceeding of SPIE* [illegible]

[illegible] *IEEE Photon. Technol. Lett.* [illegible]