中国激光

基于虚拟游标增敏的法布里-珀罗温度传感器

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摘要 针对干涉型光纤传感器，提出一种利用虚拟干涉仪实现灵敏度可调控的光学游标增敏方法，并将其应用于光纤法布里-珀罗(FP)温度传感器的增敏测量中。通过将拉锥光纤插入封有UV胶的毛细管中制得所设计的温度传感器，利用UV胶在不同温度下的体积膨胀与收缩改变FP腔长，使其干涉谱发生漂移，从而实现温度测量。根据干涉公式得到虚拟干涉谱，该虚拟干涉谱与温度传感器干涉谱叠加后产生并联式光学游标效应，通过测量叠加谱包络的漂移实现温度的增敏测量。在分析游标增敏原理的基础上，通过改变双腔长度，对游标包络的放大情况进行了仿真，制备出温度传感器样品，通过实验实现了多种温度灵敏度的调控，验证了该增敏方法的可行性。该游标增敏方法避免了实体参考干涉仪引入的误差，且灵敏度调控更加灵活和准确，具有较好的应用前景。

关键词 传感器；光纤传感器；法布里-珀罗干涉仪；游标效应；温度测量

中图分类号 TP212.1 **文献标志码** A **DOI**：10.3788/CJL220998

1 引言

近些年，光纤传感技术因具有高灵敏度、防腐蚀、质量轻、不受电磁干扰、体积小、测量带宽宽等优点而走入人们的视野，成为了科研人员炙手可热的研究对象[1-7]。光纤传感技术目前已被广泛应用于温度[8]、压力[9]、应变[10]、折射率[11]等参数的测量中。在各种物理量中，温度在日常生活和生产中起着非常重要的作用。光纤干涉仪作为高精度测量技术增加了温度测量的准确性。

近年来，游标效应增敏方案[12-13]得到广泛研究并被应用到温度传感器的研究中。2020年，文献[14]使用两个长度略有不同的级联光纤环，制作出一种基于级联游标的光纤环微波光子滤波器(MPF)温度传感器，并通过实验验证，级联光纤环温度传感器的灵敏度(528.5 pm/℃)比单光纤环温度传感器提高了约30倍。2019年，文献[15]将单模光纤-空芯光子晶体光纤-玻璃板串联，制备出一种游标增敏型光纤法布里-珀罗干涉仪(IFFPI)高温传感器，其游标效应由单模光纤(SMF)-光子晶体光纤(PCF)拼接接头和折叠空芯-光子晶体光纤(HC-PCF)尖端两端的两个空气/玻璃界面反射的三束光形成，该传感器的温度灵敏度为15.68 pm/℃，通过缩短纯二氧化硅尖端的长度，进一步提高了温度灵敏度。2021年，文献[16]提出了一种基于光纤Sagnac干涉仪和偏振模干涉仪级联结构的高灵敏光纤温度传感器，将对温度不敏感的椭圆芯保偏光纤引入到Sagnac环内以制备参考干涉仪，为传感干涉仪提供了一个基于光学游标效应的“定标主尺”，实现了15.56 nm/℃的温度灵敏度，是单个偏振模干涉仪温度灵敏度的11.12倍。2022年，文献[17]设计并制备了一种基于PDMS膜封装空芯光纤的级联双腔温度传感器，该传感器由空气腔和聚二甲基硅氧烷(PDMS)腔级联而成，空气腔与复合腔(由空气腔和PDMS组成)之间产生游标效应，与全光纤级联双腔温度传感器相比，实现了1.32 nm/℃的温度灵敏度。由此可见，基于游标增敏的温度传感器的灵敏度得到显著提高，但游标干涉仪自身不稳定会引入测量误差。

本文提出了一种光学游标增敏方案以实现光纤法布里-珀罗温度传感器灵敏度的可调控，即利用传感干涉仪光谱与虚拟干涉仪光谱并联叠加产生的游标效应来实现温度的增敏测量。根据干涉公式仿真研究了干涉仪腔长对游标包络的影响，并通过实验验证了该方案的可行性，实现了温度灵敏度的可控调节，且温度灵敏度误差较小。所提出的虚拟参考干涉仪有效避免了引入的实体参考干涉仪导致的测量误差，具有可行性且稳定性较好。

收稿日期：2022-06-27；**修回日期**：2022-08-14；**录用日期**：2022-09-01；**网络首发日期**：2022-09-11

基金项目：国家自然科学基金青年项目(11904262)、天津市教委科研计划项目(2019KJ016)、天津市“项目＋团队”重点培养专项(XB202007)

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2 传感器原理分析及制作

2.1 温度传感器的结构与制备

本文所设计的光纤法布里-珀罗(FP)温度传感器结构如图1所示，M_1和M_2分别是传感干涉仪传感腔的两个反射面，I_1和I_2分别是反射面M_1和M_2的反射光强度。由于所用的传感腔是空气腔，两个反射面的反射率均小于4%，因此从光源发出的光经过两个反射面后，反射光可视为双光束干涉[18]。其光强表达式为

$$I=I_1+I_2+2\sqrt{I_1I_2}\cos\left(\frac{4\pi nL}{\lambda}+\varphi_0\right),\qquad(1)$$

式中：$I_1=R_1$，$I_2=(1-R_1)(1-k)$，R_1和R_2分别是反射面M_1和M_2的反射率，k是传感腔总的传输损耗；λ是入射光在真空中的波长；n是传感腔内介质的折射率；L是传感腔的腔长；φ_0是入射光的初始相位。传感干涉仪填充的UV胶具有高热膨胀系数，因此随着温度的升高，胶体迅速膨胀，传感干涉仪腔长减小，光谱发生偏移。

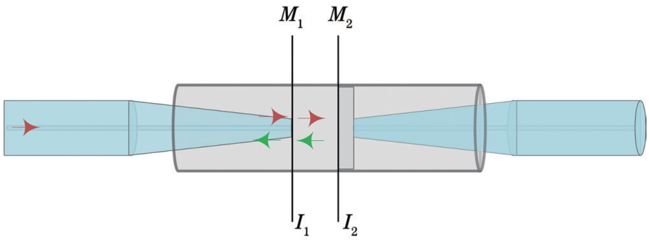

图1 法布里-珀罗传感干涉仪结构与原理图

Fig. 1 Structure and schematic of FP interferometer

该温度传感器的制造过程如图2所示。第一步：利用光纤微纤维加工平台，对一段去除涂层的单模光纤进行拉锥，锥区长度为3000 μm，锥腰直径为115 μm，并选择合适的位置进行切割。第二步：用微流泵将UV胶注入到毛细管(内径为130 μm，外径为200 μm)中，胶长430 μm后停止注射，用UV灯固化2 h；第三步：将准备好的SMF圆锥体分别插入毛细管两端，输入端圆锥体和胶面保持120 μm距离以作为FP腔，将输出端和胶面平面连接并焊接固定。

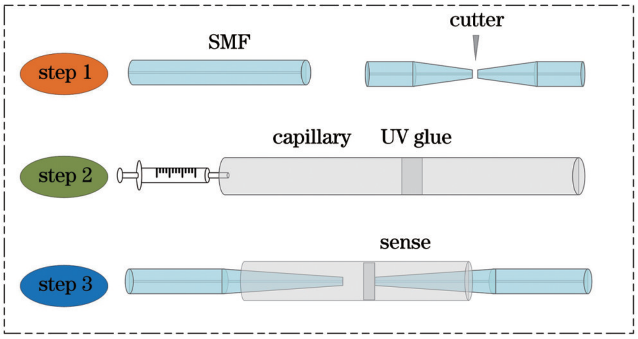

图2 法布里-珀罗传感干涉仪的制备流程

Fig. 2 Fabrication process of FP sensing interferometer

2.2 光学游标效应增敏原理及仿真

为提高温度检测的灵敏度，采用并联光学游标增敏方法，即并联叠加自由光谱范围相近的两个干涉仪光谱，改变干涉峰的包络，产生游标包络光谱，包络峰在目标参数变化下表现出均匀的波长偏移，通过计算包络波长偏移量响应，实现被测量的增敏效果。为了避免实体参考干涉仪引入的误差并实现灵敏度可调控，本文采用虚拟参考干涉仪，即根据干涉谱理论公式仿真得到参考干涉仪的干涉谱，将其与采集到的传感干涉仪干涉谱叠加，产生光学游标效应。

光束在光纤中以极小的角度入射，此时初始相位设为0°，则传感干涉仪反射光强[18-19]可表示为

$$I_{\mathrm{S}}=I_3+I_4+2\sqrt{I_3I_4}\cos\left(\frac{4\pi n_{\mathrm{S}}L_{\mathrm{S}}}{\lambda}\right),\qquad(2)$$

虚拟参考干涉仪反射光强为

$$I_{\mathrm{VR}}=I_5+I_6+2\sqrt{I_5I_6}\cos\left(\frac{4\pi n_{\mathrm{VR}}L_{\mathrm{VR}}}{\lambda}\right),\qquad(3)$$

式中：I_3和I_4分别表示传感干涉仪腔内两个反射面的反射光强；I_5和I_6分别表示虚拟参考干涉仪腔内两个反射面的反射光强；L_{S}和L_{VR}分别表示传感干涉仪和虚拟参考干涉仪腔长；n_{S}和n_{VR}分别是传感干涉仪腔内介质的折射率和参考干涉仪腔内介质的折射率。

当传感干涉仪与虚拟参考干涉仪光谱叠加后，总干涉光强I_1[19]为

$$I_1=I_{\mathrm{S}}+I_{\mathrm{VR}}=I_3+I_4+I_5+I_6+2\sqrt{I_3I_4}\cos\left(\frac{4\pi n_{\mathrm{S}}L_{\mathrm{S}}}{\lambda}\right)+2\sqrt{I_5I_6}\cos\left(\frac{4\pi n_{\mathrm{VR}}L_{\mathrm{VR}}}{\lambda}\right)。\qquad(4)$$

由光学游标效应理论可知，叠加后干涉光谱的包络函数[20]为

$$I=A+B\cos\left[\frac{4\pi(L_{\mathrm{S}}-L_{\mathrm{VR}})}{\lambda}\right],\qquad(5)$$

式中：A为叠加谱包络的直流分量；B为叠加谱包络的振幅。

叠加谱包络的自由光谱范围远大于单个传感干涉仪干涉光谱的自由光谱范围，叠加谱包络的自由光谱范围(F_{E})可以表示为

$$F_{\mathrm{E}}=\frac{F_{\mathrm{S}}\times F_{\mathrm{VR}}}{|F_{\mathrm{S}}-F_{\mathrm{VR}}|},\qquad(6)$$

式中：F_{S}和F_{VR}分别表示传感干涉仪与虚拟参考干涉仪的自由光谱范围。

传感干涉仪与虚拟参考干涉仪叠加后并联游标干涉仪的温度灵敏度(S_{E})表示为

$$\begin{aligned}S_{\mathrm{E}}&=\frac{2}{m}\left(n\frac{\partial L_{\mathrm{S}}}{\partial T}\right)\frac{F_{\mathrm{S}}}{F_{\mathrm{S}}-F_{\mathrm{VR}}}=\\&\frac{\lambda_m}{nL_{\mathrm{S}}}\left(n\frac{\partial L_{\mathrm{S}}}{\partial T}\right)\times\frac{F_{\mathrm{S}}}{F_{\mathrm{S}}-F_{\mathrm{VR}}}=\qquad(7)\\&\lambda_m(\eta-\xi)\times\frac{F_{\mathrm{S}}}{F_{\mathrm{S}}-F_{\mathrm{VR}}},\end{aligned}$$

式中：λ_m是第m阶波谷对应的波长；T是温度；η是UV胶的热膨胀系数；ζ是石英毛细管的热膨胀系数。温度也会改变空气的折射率，但可以忽略不计。

当传感干涉仪与参考干涉仪叠加时，叠加谱包络漂移对应温度的灵敏度为

$$\frac{\Delta F_{\mathrm{E}}}{\Delta X}=\lambda_{\mathrm{s}\text{-}m}\left(\frac{1}{n}\frac{\Delta n}{\Delta X}+\frac{1}{L_{\mathrm{s}}}\frac{\Delta L_{\mathrm{s}}}{\Delta X}\right)\frac{F_{\mathrm{VR}}}{F_{\mathrm{VR}}-F_{\mathrm{S}}}, \tag{8}$$

式中：ΔF_{E}为干涉包络的光谱变化量；ΔX为传感量的变化量；$\lambda_{\mathrm{s}\text{-}m}$为第$m$阶次的峰值波长；$\Delta L_{\mathrm{s}}$为传感腔腔长变化量；$\Delta n$为折射率变化量。当双腔变化（传感腔腔长变化而参考腔腔长不变化）时，相对于单一FP传感干涉仪的灵敏度，叠加后游标干涉光谱的放大倍数可以表示为

$$M_1=\frac{F_{\mathrm{E}}}{F_{\mathrm{S}}}=\frac{F_{\mathrm{VR}}}{F_{\mathrm{VR}}-F_{\mathrm{S}}}=\frac{n_{\mathrm{VR}}L_{\mathrm{VR}}}{n_{\mathrm{VR}}L_{\mathrm{VR}}-n_{\mathrm{S}}L_{\mathrm{S}}}。\tag{9}$$

如果参考腔腔长变化而传感腔腔长不变化，则灵敏度的增大倍数为

$$M_2=\frac{F_{\mathrm{E}}}{F_{\mathrm{VR}}}=\frac{F_{\mathrm{S}}}{F_{\mathrm{S}}-F_{\mathrm{VR}}}=\frac{n_{\mathrm{S}}L_{\mathrm{S}}}{n_{\mathrm{S}}L_{\mathrm{S}}-n_{\mathrm{VR}}L_{\mathrm{VR}}}。\tag{10}$$

根据式(9)、(10)，下面仿真研究双腔长度对反射光谱和游标包络的影响。设光纤的折射率为1.4682，腔内介质折射率为1，本仿真实验均在1550 nm附近进行研究，设置传感干涉仪的腔长$L_{\mathrm{S}}=200\ \mu\mathrm{m}$，参考干涉仪的腔长$L_{\mathrm{VR}}=150\ \mu\mathrm{m}$，则$F_{\mathrm{S}}=6\ \mathrm{nm}$，$F_{\mathrm{VR}}=8\ \mathrm{nm}$，$F_{\mathrm{E}}=24\ \mathrm{nm}$，并由式(9)、(10)得知游标包络$F_{\mathrm{E}}$分别为$F_{\mathrm{S}}$和$F_{\mathrm{VR}}$的4倍和3倍。

当传感腔长不变而参考腔长变化时，L_{VR}从150 μm增加到151 μm，如图3(a)所示，在1550 nm附近，参考干涉仪干涉光谱的波谷向长波长方向漂移2 nm，干涉光谱包络的波谷向短波长方向漂移6 nm；L_{VR}从150 μm减小到149 μm，如图3(b)所示，在1550 nm附近，参考干涉仪干涉光谱的波谷向短波长方向漂移2 nm，干涉光谱包络的波谷向长波长方向漂移6 nm。

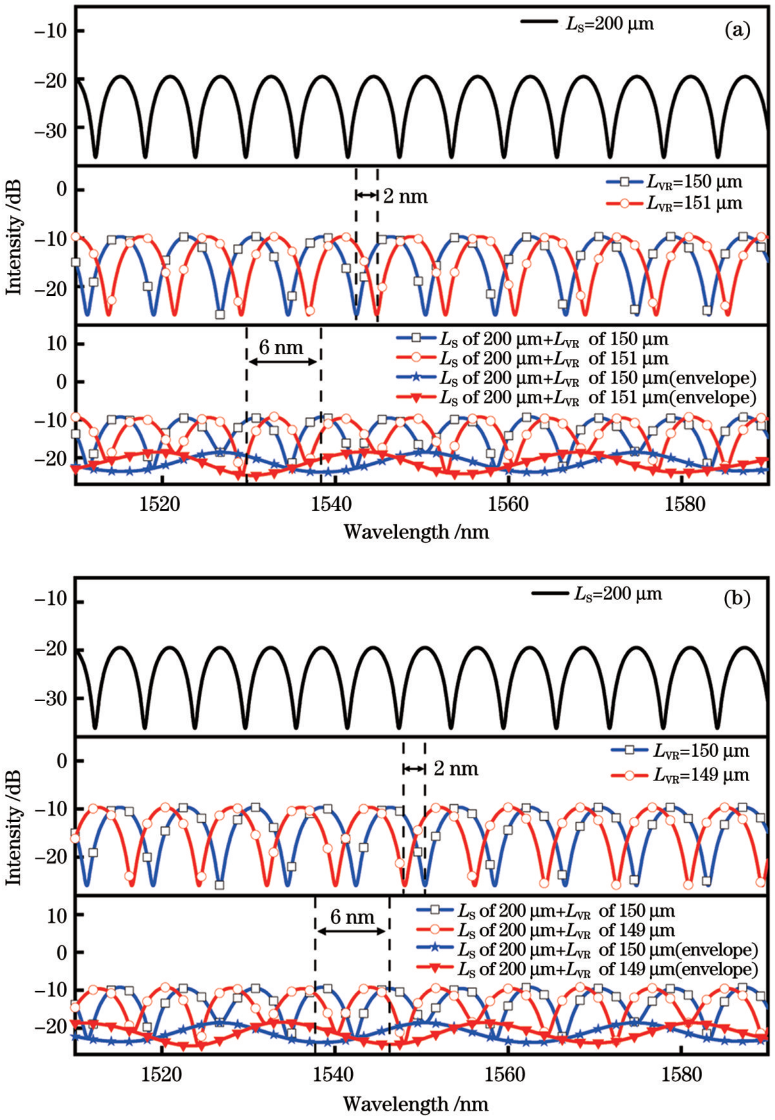

图3　参考腔腔长变化对光谱的影响。(a)腔长增大；(b)腔长减小

Fig. 3　Effects of length change of reference cavity on spectrum. (a) Increasing cavity length; (b) reducing cavity length

当传感腔长变化而参考腔长不变时，L_S从200 μm增加到201 μm，如图4（a）所示，在1550 nm附近，传感干涉仪干涉光谱的波谷向长波长方向漂移2 nm，干涉光谱包络的波谷向长波长方向漂移8 nm；L_S从200 μm减小到199 μm，如图4（b）所示，在1550 nm附近，传感干涉仪干涉光谱的波谷向短波长方向漂移2 nm，干涉光谱包络的波谷向短波长方向漂移8 nm。

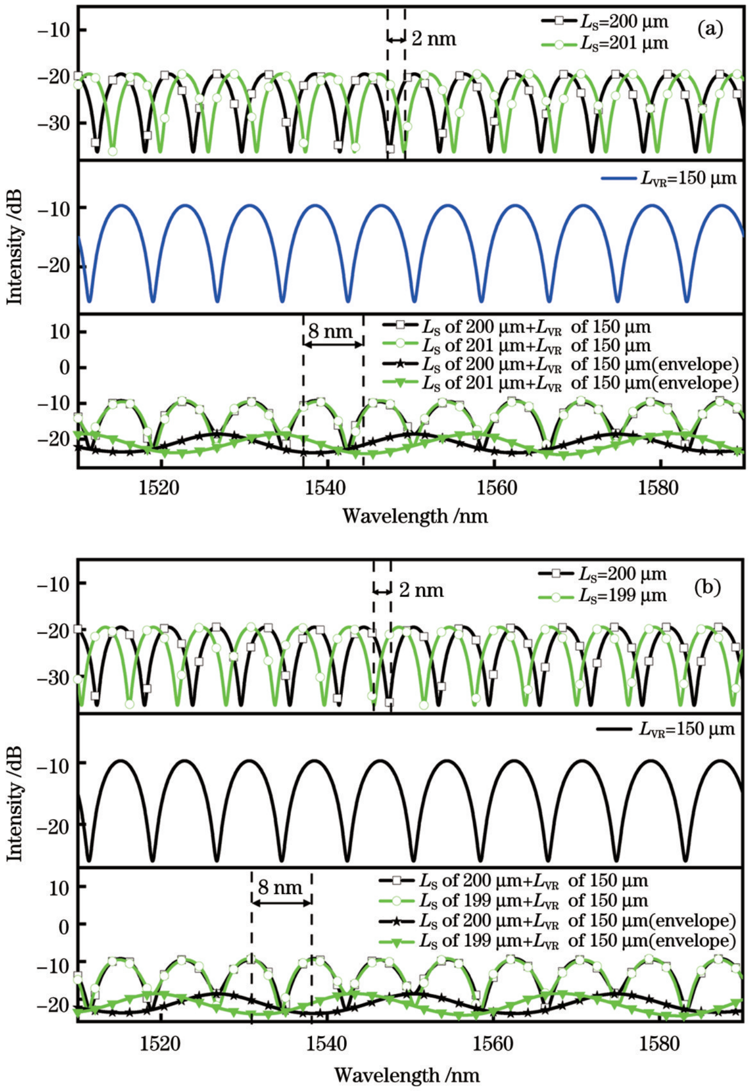

图4　传感腔腔长变化对光谱的影响。（a）腔长增大；（b）腔长减小

Fig. 4　Effects of length change of sensing cavity on spectrum. (a) Increasing cavity length; (b) reducing cavity length

综上所述，当传感干涉仪的自由光谱范围大于参考干涉仪的自由光谱范围（$F_S > F_{VR}$）时，升高温度，传感干涉仪腔长变小，传感干涉仪的光谱向左漂移，干涉光谱包络向左漂移；当传感干涉仪的自由光谱范围小于参考干涉仪的自由光谱范围（$F_S < F_{VR}$）时，升高温度，传感干涉仪腔长变小，传感干涉仪的光谱向左漂移，干涉光谱包络向右漂移。光谱仿真实验结果验证了游标包络的放大理论，同时为后续实验提供了支撑。

3　实验

3.1　装置

虚拟游标增敏的FP温度传感器的实验装置如图5所示，通过3 dB耦合器将传感干涉仪与宽带光源、光谱分析仪连接，最后在数据处理阶段叠加传感干涉仪与虚拟参考干涉仪的干涉光谱。

3.2　无游标下的温度测量

传感干涉仪在51 ℃时的干涉光谱及空间频谱如图6所示，空间频谱曲线为干涉光谱的快速傅里叶变换（FFT），曲线中只有一个主峰，该峰后的其他峰都为基频的倍频或混频成分。已知峰值点的横坐标是自由光谱范围的倒数，得出$F_S = 10$ nm，与实验所得传感干涉仪$F_S = 10$ nm相符合。因此可以确定该传感干涉仪为双光束干涉。

将传感干涉仪放置在控温平台上，经3 dB耦合器与宽带光源、光谱分析仪连接。以1 ℃为步长调节控

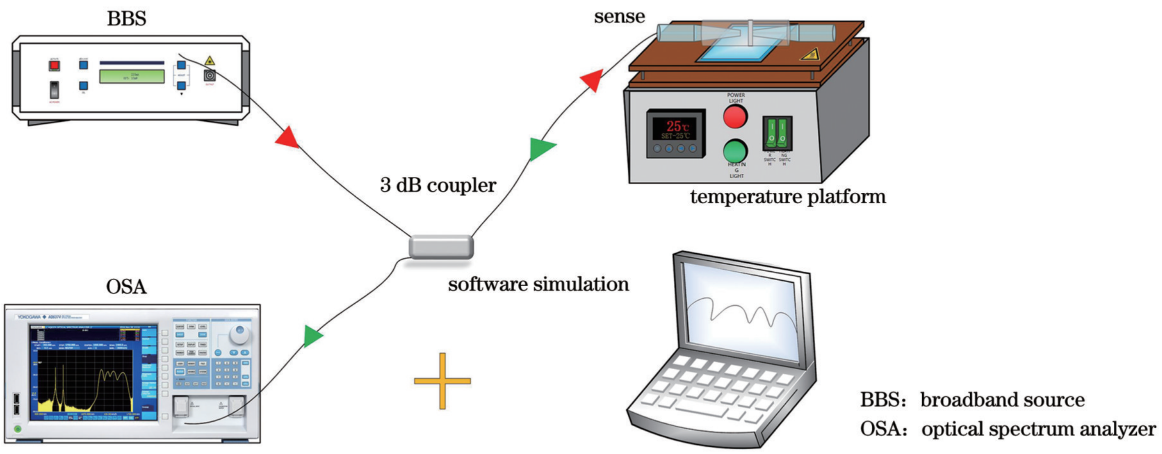

图 5 虚拟并联型游标温度传感器的实验装置示意图

Fig. 5 Experimental device diagram of virtual parallel vernier temperature sensor

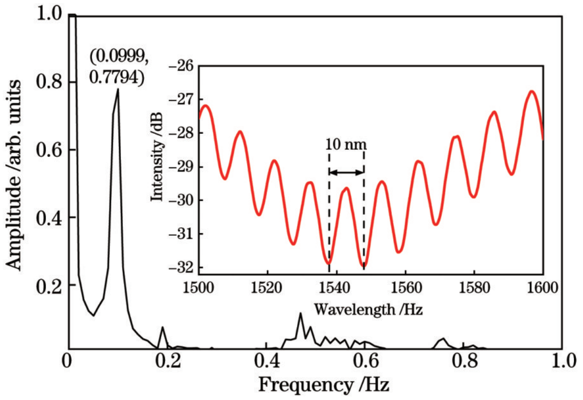

图 6 传感干涉仪在 51 ℃下的空间频谱，插图为传感干涉仪在 51 ℃下的干涉光谱

Fig. 6 Spatial spectrum of sensing interferometer at 51 ℃ with interference spectrum of sensing interferometer at 51 ℃ shown in inset

温平台，温度从 51 ℃逐步升高到 55 ℃，每达到一个设定温度后，保持 10 min，待温度稳定后由光谱分析仪记录下反射光谱。在不同温度下获得的反射光谱如图 7(a)所示，随着温度的升高，反射光谱的共振波长呈现蓝移趋势；图 7(b)为不同温度下传感干涉仪的光谱波谷与温度的线性拟合结果。已知传感干涉仪的自由光谱范围为 10 nm，由图 7 得出，在波谷点 1 处温度灵敏度为 2.015 nm/℃，线性度为 0.999，则干涉谷波长与温度具有较好的线性拟合度。此外，该传感器的温度测量范围与干涉谱的自由光谱范围有关，为避免发生光谱波谷点混淆，光谱波谷点的漂移被限制在 1 个自由光谱范围内，因此图 7 所示的传感器温度测量范围仅为 5 ℃左右，可通过制备更小腔长的传感器来增大自由光谱范围，可获得更大的测量范围。

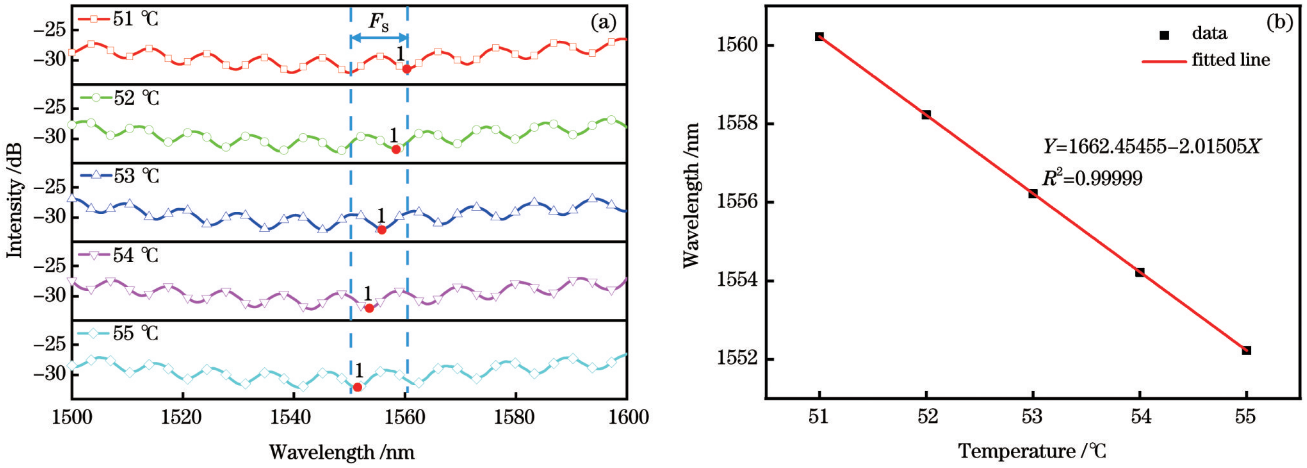

图 7 传感干涉仪温度测量实验结果。(a)51～55 ℃范围内的光谱；(b)波谷点 1 处的拟合结果

Fig. 7 Experimental results of temperature measurement for sensing interferometer. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point 1

将传感干涉仪样品放置在控温平台上，温度设置为 51 ℃，并使用商用测温仪探头进行监测，待温度稳定后，每隔 10 min 记录一次数据，60 min 内的重复测量结果如图 8 所示，其均值为 1550.015 nm，标准差为 0.082 nm，目标光谱波谷点相对均值的最大偏移为 0.115 nm，所引起的温度误差约为 0.06 ℃。可见，该

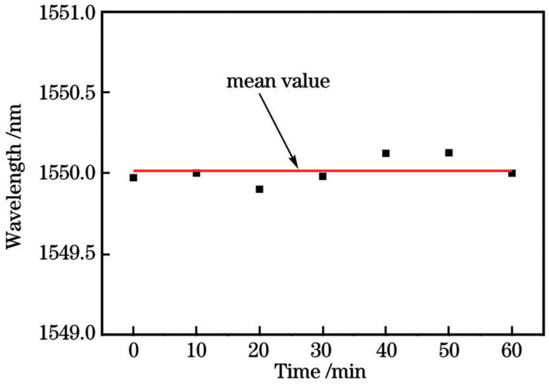

图 8　51 ℃温度下目标波谷点重复测量的结果

Fig. 8　Repeated measurement result of target valley point at 51 ℃

传感器具有较好的测量重复性。

3.3　基于虚拟参考干涉仪的可调温度灵敏度实验

把虚拟参考干涉仪的参考腔腔长 L_{VR} 分别设置为 180、160、150、144、140 μm，通过式(10)可知，在传感干涉仪与虚拟参考干涉仪叠加后，理论上可以分别实现温度灵敏度 2、3、4、5、6 倍左右的放大。图 9~13 依次展示了叠加后干涉光谱的变化情况以及干涉光谱的游标包络波谷点的线性拟合情况。当温度升高时，干涉包络光谱的共振波长呈红移趋势；腔长分别为 180、160、150、144 、140 μm 时，其温度灵敏度分别为 4.018、6.021、8.009、10.033、12.096 nm/℃。

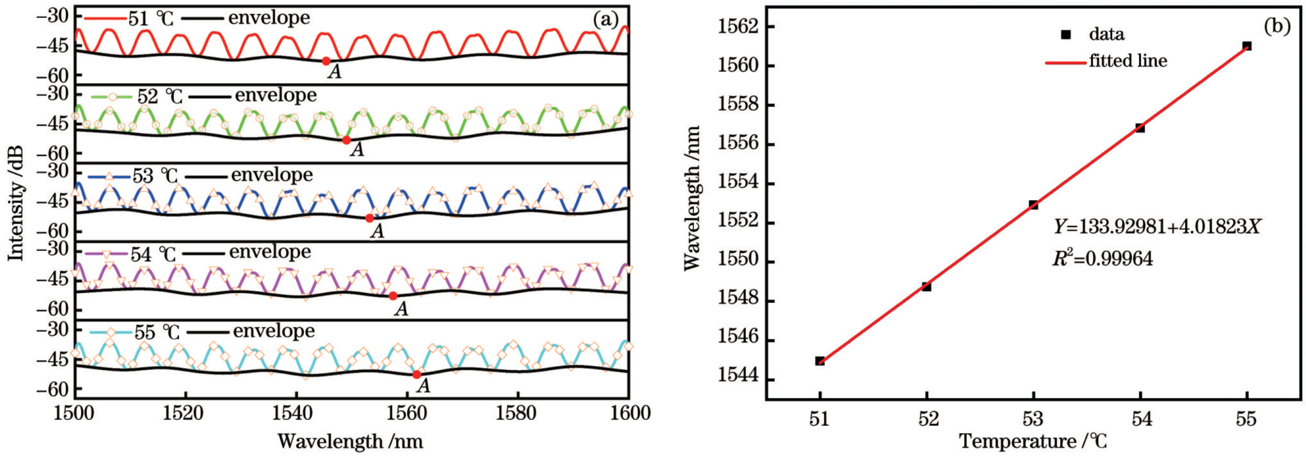

图 9　$L_{\mathrm{VR}}=180$ μm 时虚拟参考干涉仪温度测量实验结果。(a)51~55 ℃范围内的光谱；(b)包络谱波谷点 *A* 处的拟合结果

Fig. 9　Experimental results of temperature measurement for virtual reference interferometer when $L_{\mathrm{VR}}=180$ μm. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point *A* of envelope spectrum

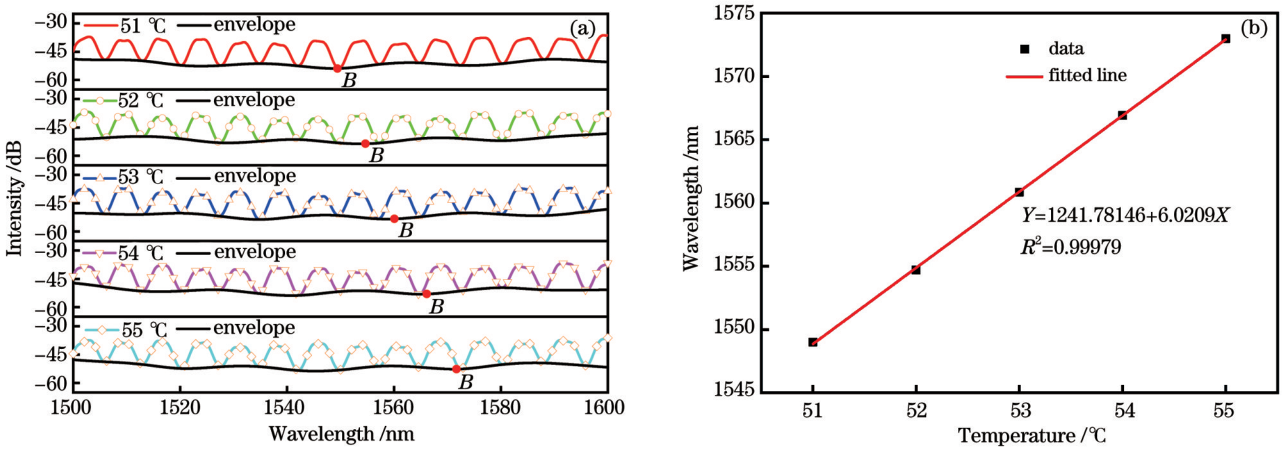

图 10　$L_{\mathrm{VR}}=160$ μm 时虚拟参考干涉仪温度测量实验结果。(a)51~55 ℃范围内的光谱；(b)包络谱波谷点 *B* 处的拟合结果

Fig. 10　Experimental results of temperature measurement for virtual reference interferometer when $L_{\mathrm{VR}}=160$ μm. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point *B* of envelope spectrum

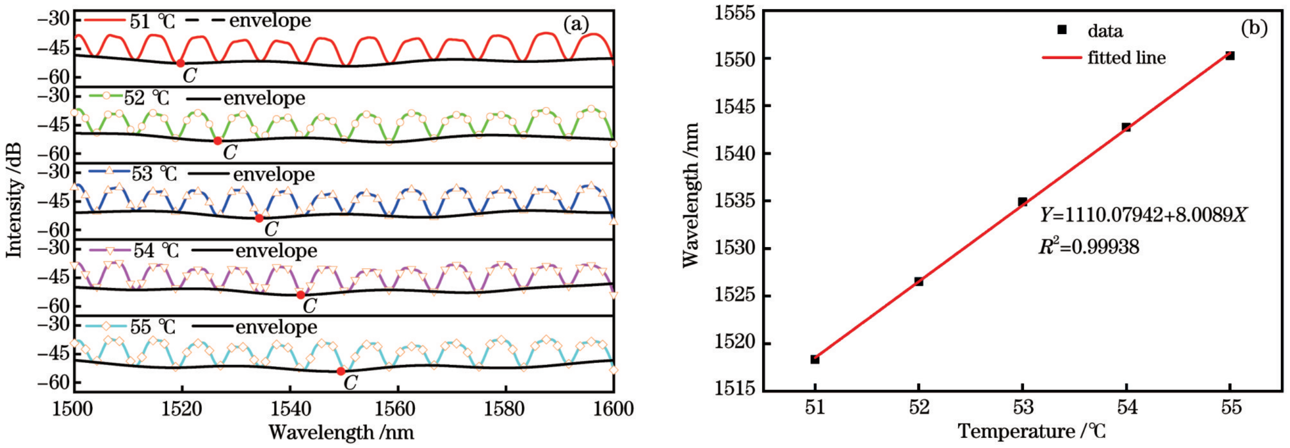

图11 $L_{\mathrm{VR}}=150\ \mu\mathrm{m}$时虚拟参考干涉仪温度测量实验结果。(a)51～55 ℃范围内的光谱；(b)包络谱波谷点C处的拟合结果

Fig. 11 Experimental results of temperature measurement for virtual reference interferometer when $L_{\mathrm{VR}}=150\ \mu\mathrm{m}$. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point C of envelope spectrum

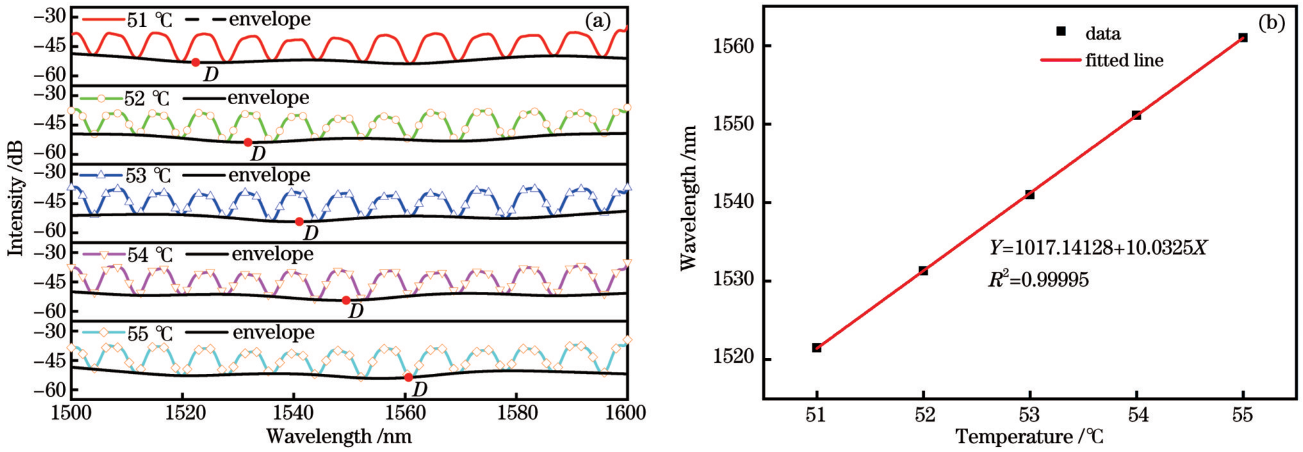

图12 $L_{\mathrm{VR}}=144\ \mu\mathrm{m}$时虚拟参考干涉仪温度测量实验结果。(a)51～55 ℃范围内的光谱；(b)包络谱波谷点D处的拟合结果

Fig. 12 Experimental results of temperature measurement for virtual reference interferometer when $L_{\mathrm{VR}}=144\ \mu\mathrm{m}$. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point D of envelope spectrum

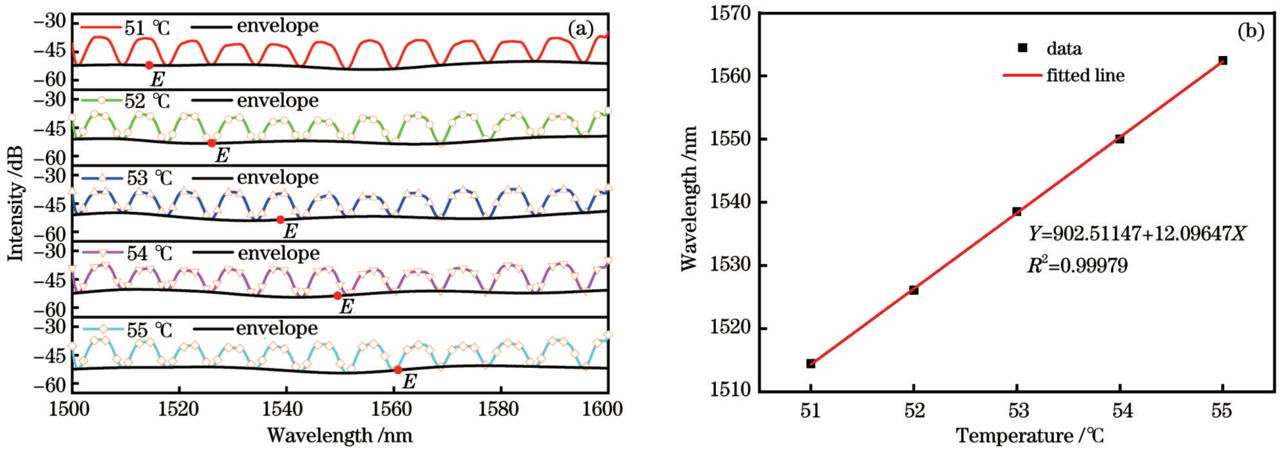

图13 $L_{\mathrm{VR}}=140\ \mu\mathrm{m}$时虚拟参考干涉仪温度测量实验结果。(a)51～55 ℃范围内的光谱；(b)包络谱波谷点E处的拟合结果

Fig. 13 Experimental results of temperature measurement for virtual reference interferometer when $L_{\mathrm{VR}}=140\ \mu\mathrm{m}$. (a) Spectra in range of 51–55 ℃; (b) fitting result at valley point E of envelope spectrum

相比于单个传感干涉仪，灵敏度分别放大了1.994、2.988、3.975、4.979、6.003倍，且干涉波谷A点、B点、C点、D点、E点都具有较好的线性拟合度。如表1所示，温度灵敏度放大了2、3、4、5、6倍左右。

表1　基于游标效应的法布里-珀罗干涉仪的温度灵敏度

Table 1　Temperature sensitivity of FP interferometer based on vernier effect

Parameter	Sensing interferometer	Virtual parallel FP interferometer				
Temperature /℃	51–55	51–55	51–55	51–55	51–55	51–55
L_{VR} /μm	–	180	160	150	144	140
Sensitivity /(nm·℃$^{-1}$)	2.015	4.018	6.021	8.009	10.033	12.096
Theoretical magnification factor	–	2	3	4	5	6
Actual magnification factor	–	1.994	2.988	3.975	4.979	6.003
Amplification error	–	0.006	0.012	0.025	0.021	0.003

4　结　论

利用虚拟干涉仪通过光学游标增敏方法实现了FP传感器的温度灵敏度调控。根据传感公式研究了游标包络的放大原理，对不同双腔长度下的叠加光谱进行了包络漂移仿真，在虚拟参考干涉仪腔长改变的情况下，通过实验实现了温度灵敏度2～6倍的放大调控，验证了该光学游标增敏方案。这种虚拟仿真方法使测量过程中的参考干涉仪不受外界环境的影响，增加了温度的灵敏度。该方法不需要对干涉仪进行额外的修改，也适用于其他干涉型光纤传感器，在现有光纤传感器网络的增敏改造中具有显著优势。

参　考　文　献

[1] Liao H, Lu P, Fu X, et al. Sensitivity amplification of fiber-optic in-line Mach-Zehnder Interferometer sensors with modified Vernier-effect[J]. Optics Express, 2017, 25(22): 26898-26909.

[2] Yang Y Q, Ge W, Jiang J X, et al. Sensitivity-enhanced Sagnac interferometer temperature sensor based on Vernier effect with the help of Fabry-Perot interferometer[C]∥ 2017 16th International Conference on Optical Communications and Networks (ICOCN), August 7-10, 2017, Wuzhen, China. New York: IEEE Press, 2017.

[3] Xu Z L, Luo Y Y, Sun Q Z, et al. Refractive index sensor based on theta-shaped microfiber resonator and Vernier effect[J]. Proceedings of SPIE, 2017, 10323: 103233N.

[4] Zhang Y X, Xu B, Wang D N, et al. Sensitivity-enhanced fiber strain sensing system based on microwave frequency scanning with the Vernier effect[J]. Optical Fiber Technology, 2018, 43: 175-179.

[5] 韩智天. 高灵敏度光纤干涉型传感器的应用研究[D]. 南京：南京邮电大学，2019.
Han Z T. The application study on highly sensitive optical fiber interference sensor[D]. Nanjing: Nanjing University of Posts and Telecommunications, 2019.

[6] 张亮. 基于游标效应和光程差放大的光纤传感增敏机理研究[D]. 武汉：华中科技大学，2014.
Zhang L. Study on sensitization mechanism of optical fiber sensor based on vernier effect and optical path difference amplification[D]. Wuhan: Huazhong University of Science and Technology, 2014.

[7] Cai W J, Yu S D, Zhang Y C, et al. Enhanced temperature sensing based on birefringence induced Vernier effect in a symmetrical metal-cladding waveguide[J]. Journal of Modern Optics, 2020, 67(12): 1053-1058.

[8] 范维文，万洪丹，陈彧芳，等. 基于二模-单模微纳光纤Sagnac环的高灵敏度光纤温度传感器[J]. 光学学报，2022，42(16): 1606001.
Fan W W, Wan H D, Chen Y F, et al. Highly sensitive fiber optic temperature sensor based on two-mode-single-mode microfiber Sagnac loop[J]. Acta Optica Sinica, 2022, 42(16): 1606001.

[9] Vengal Rao P, Srimannarayana K, Sai Shankar M, et al. A diaphragm based low-cost fiber optic pressure sensor[J]. Microwave and Optical Technology Letters, 2012, 54(10): 2229-2231.

[10] Liu P D, Huang W Z, Zhang W T, et al. Ultrahigh resolution optic fiber strain sensor with a frequency-locked random distributed feedback fiber laser[J]. Optics Letters, 2018, 43(11): 2499-2502.

[11] Nasirifar R, Danaie M, Dideban A. Dual channel optical fiber refractive index sensor based on surface plasmon resonance[J]. Optik, 2019, 186: 194-204.

[12] Gomes A D, Bartelt H, Frazão O. Optical vernier effect: recent advances and developments[J]. Laser & Photonics Reviews, 2021, 15(7): 2000588.

[13] Gao H T, Wang J X, Shen J, et al. Study of the vernier effect based on the Fabry-Perot interferometer: methodology and application[J]. Photonics, 2021, 8(8): 304.

[14] Lei X Q, Dong X P. High-sensitivity Fabry-Perot interferometer high-temperature fiber sensor based on vernier effect[J]. IEEE Sensors Journal, 2020, 20(10): 5292-5297.

[15] Wang Z R, Huang L, Liu C, et al. Sensitivity-enhanced fiber temperature sensor based on vernier effect and dual in-line Mach-Zehnder interferometers[J]. IEEE Sensors Journal, 2019, 19(18): 7983-7987.

[16] 方莎莎，吴许强，张刚，等. 基于游标效应的高灵敏光纤温度和应变传感器[J]. 中国激光，2021，48(1): 0106004.
Fang S S, Wu X Q, Zhang G, et al. High-sensitivity fiber optic temperature and strain sensors based on the vernier effect[J]. Chinese Journal of Lasers, 2021, 48(1): 0106004.

[17] 徐廷廷，杨玉强，杨文龙，等. 基于PDMS膜封装空芯光纤的级联双腔温度传感器[J]. 光学学报，2022，42(8): 0806004.
Xu T T, Yang Y Q, Yang W L, et al. Cascaded double-cavity temperature sensor based on hollow fibers encapsulated by PDMS membrane[J]. Acta Optica Sinica, 2022, 42(8): 0806004.

[18] Nan T, Liu B, Wu Y F, et al. Ultrasensitive strain sensor based on Vernier-effect improved parallel structured fiber-optic Fabry-Perot interferometer[J]. Optics Express, 2019, 27(12): 17239-17250.

[19] Gao H T, Wang J X, Shen J, et al. Study of the vernier effect based on the Fabry-Perot interferometer: methodology and application[J]. Photonics, 2021, 8(8): 304.

[20] Zhang P, Tang M, Gao F, et al. Cascaded fiber-optic Fabry-Perot interferometers with Vernier effect for highly sensitive measurement of axial strain and magnetic field[J]. Optics Express, 2014, 22(16): 19581-19588.

Fabry-Perot Temperature Sensor Based on Virtual Vernier Sensitization

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Abstract

Objective Optical fiber sensing technology has attracted attention because of its high sensitivity, corrosion resistance, immunity to electromagnetic interference, small size, and wide measurement bandwidth. Temperature plays a significant role in daily life and various applications; particularly, the controllability and accuracy of temperature sensitivity in biological protein activity and medical experiments are essential. Among them, the method of increasing temperature sensitivity through the vernier effect is widely used in optical fiber sensors. The optical vernier effect can be achieved using a sensing interferometer and a reference interferometer. The reference interferometer, which is not sensitive to temperature, provides a 'calibration master ruler' to the sensing interferometer based on the optical vernier effect, thereby amplifying the temperature sensitivity, as opposed to using a single sensing interferometer. However, the instability of the interferometer can result in measurement errors. Therefore, this study proposes using a virtual reference interferometer for achieving a sensitivity-tunable optical vernier effect to increase the temperature sensitivity. This method is applied to the Fabry-Perot (FP) temperature sensor based on UV glue, and the sensitization effect of its temperature sensitivity is verified through experiments. Subsequently, the feasibility of realizing the increase of temperature sensitivity is demonstrated.

Methods Theoretically, the principle of the vernier effect sensitization is derived from the interference formula. Therefore, the amplification of the vernier envelope is simulated by changing the cavity length of the sensing interferometer or that of the reference interferometer. It is verified that the increase in sensitivity can be achieved using the virtual vernier interferometer, and this sensitivity can be regulated by changing the cavity length. Experimentally, the FP temperature sensor is fabricated by inserting a tapered optical fiber into a capillary tube with UV glue. The UV glue expands and contracts at different temperatures, resulting in a change in the cavity length and a drift in the superimposed spectrum. In the experiment, various temperature sensitivities are controlled by changing the cavity length of the reference interferometer. The feasibility of the scheme is verified.

Results and Discussions Based on the principle of increased sensitivity based on the vernier effect, when the cavity length of the sensing interferometer or reference interferometer is changed, the superimposed vernier interference envelope spectrum achieves a certain multiple of sensitivity amplification, compared to that achieved using single FP sensing interferometer. Subsequently, by the spectral simulation of the double cavity length, it is deduced that when the free spectral range of the sensing interferometer is larger than that of the reference interferometer, the cavity length of the sensing interferometer decreases with increasing temperature, and the spectrum moves to the left drift, whereas the interference spectral envelope drifts to the left. When the free spectral range of the sensing interferometer is smaller than that of the reference interferometer, the cavity length of the sensing interferometer decreases with increasing temperature and the spectrum shifts to the left, whereas the interference spectral envelope shifts to the right (Figs. 3 and 4). Therefore, the temperature sensitivity can be controlled by introducing reference interferometers with different cavity lengths without changing the sensing interferometer. In the experiment, according to the theoretical formula, the cavity lengths of the relevant reference interferometers are set as 180, 160, 150, 144, and 140 μm, respectively, and their temperature sensitivities are 4.018, 6.021, 8.009, 10.033, and 12.096. It is inferred through experiments that, compared with the single sensing interferometer with a temperature sensitivity of 2.015 nm/℃, the FP temperature sensor based on the virtual vernier achieves 2–6 times temperature sensitivities, which is consistent with the results obtained by the FP temperature sensor theoretically (Figs. 9–13).

Conclusions In this study, the temperature sensitivity regulation of the FP sensor is realized using the sensitization method of the optical vernier based on a virtual reference interferometer. The envelope drift simulations of the superimposed spectra with different double cavity lengths are conducted according to the amplification principle of the vernier envelope obtained from the sensing formula. In the experiment, when the cavity length of the virtual reference interferometer is changed, the control of different temperature sensitivities ranging from 2–6 times is realized, thereby verifying that the sensitization scheme of the optical vernier is feasible. This virtual simulation method not only avoids the influence of the external environment on the reference interferometer during the measurement process but also effectively increases the temperature sensitivity. This method does not require additional modification of the interferometer and can be applied to other interferometric fiber optic sensors; it has significant potential for the enhancement of existing fiber optic sensor networks.

Key words sensors; fiber optics sensors; Fabry-Perot interferometer; vernier effect; temperature measurement