光学学报

散射增强微结构光纤及其分布式传感技术研究进展

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摘要 分布式光纤传感器以光纤作为传输和传感融合的介质，具有高灵敏、全分布、大尺度、高分辨的独特优势，近年来受到多个应用领域研究人员的关注并逐步进入产业化。然而，现有普通单模光纤在传感信噪比与稳定性等方面仍存在局限性。以散射增强微结构特种光纤为传感载体，研究其分布式传感增效机理，介绍了其自动化、高效率刻写制备技术，并重点阐述了其分布式光纤传感技术研究进展与相关应用。进一步对散射增强微结构传感光纤的未来发展潜力及应用方向进行了展望。

关键词 传感器；分布式光纤传感；散射增强光纤；分布式声波传感；光频域反射技术

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1 引 言

光纤传感技术利用光波作为信息载体与传输媒介，实现对环境中信号的采集和测量[1]。分布式光纤传感作为光纤传感技术的重要分支，可实现长距离、高分辨、高灵敏的连续分布式探测，获取时空二维分布信息。相比于其他两种散射型分布式传感，基于瑞利散射的系统具有较高的后向散射功率，响应速度较快，更适合用于声波、应变等动静态信号的探测。随着资源勘探、结构健康监测、水下探测等工程应用日益增长的需求牵引，分布式光纤传感近年来得到快速发展。

目前，大多分布式传感系统通常采用普通单模光纤作为传感介质，然而其瑞利后向散射信号极其微弱，传感光信噪比较低，进而导致分布式传感系统的解调信号信噪比较低；此外，激光高相干性导致的强度衰落效应会造成传感盲区，光强度衰落还会导致多通道一致性较差；同时，由于光传输损耗的影响，普通无放大单模光纤系统在长距离远端的传感信噪比受限；并且，单模光纤后向散射信号的全连续特性还会导致系统响应带宽与传感距离相互受限[2]。因此，散射增强特种光纤被引入到基于瑞利散射的分布式传感系统中，通过连续改变光纤材料、结构或引入离散散射增强机制，在特定传感参数、传感性能等方面克服普通单模光纤的分布式传感局限性[3-5]。

本文从散射增强特种光纤角度出发，研究了其分布式传感增效机理，介绍了自动精密的连续光刻技术，并重点阐述了其光时域和光频域分布式传感系统原理。同时，总结了基于散射增强微结构传感光纤的分布式声波传感与光频域反射技术的研究进展，并综述了基于上述两种系统的典型工程应用。

2 散射增强微结构传感光纤

2.1 散射增强微结构光纤传感增效机理

普通光纤主要针对光纤通信系统而设计，作为传感载体并不是最佳选择。基于普通单模光纤的分布式声波传感（DAS）系统存在相干衰落噪声、信号一致性差等局限性，导致其传感信噪比较低，甚至出现传感盲区。为了提升传感性能，降低系统复杂度，除了可进行探测解调技术方面的探索，也可面向传感应用研究特种光纤。

DAS 的工作过程可以简单地分为两步：第一步是注入光脉冲信号并使其被瑞利散射点散射；第二步是从不同散射点散射的光信号在探测器端相干叠加。当脉冲宽度为 W 的光入射到光纤中，单个瑞利散射点的散射信号[6]可表示为

$$E_m(t)=a_m \mathrm{e}^{\mathrm{i}\varphi_m-\alpha v_{\mathrm{g}} t_m} \cdot w_{\mathrm{s}} \frac{t-t_m}{W}, \tag{1}$$

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式中：a_m为第m个散射点的后向散射强度；φ_m为第m个散射点的相位；v_g为传输光的群速度；t_m为第m个散射点的到达时间；w_s为脉冲光的脉冲形状函数；α为光纤损耗系数；t为时间。若注入光脉冲功率恒定，瑞利散射系数、后向散射因子、光纤折射率和模场面积可视为常数，后向散射信号强度[6]可简单表示为

$$a_m^2 = A\frac{d}{W}, \tag{2}$$

式中：A为常数系数；d为瑞利散射点的尺寸。光纤中瑞利散射点位置随机波动导致各个散射点产生的后向散射信号的相位也会随机分布。第m个瑞利散射点的相位信息即为传输路径上所有散射点相位的累加[6]，可表示为

$$\varphi_m = \sum_{j=1}^{m}\frac{4\pi d}{\lambda}\left[n + \Delta n(j)\right], \tag{3}$$

式中：$\Delta n(j)$为各个散射点由于随机分布引起的折射率波动。探测器接收到的信号可表示为多个瑞利散射点的干涉叠加[6]：

$$E(t) = \sum_{j=1}^{M} E_m(t), \tag{4}$$

式中：M为单个脉冲范围内所包含的散射点数。在脉冲光相干长度范围内的瑞利散射点相位大致相同时会产生较强的后向散射信号，当相位相反时会产生非常弱的后向散射信号，这导致光纤中整体的瑞利散射信号存在较大的随机波动，称为相干衰落现象，如图 1(a)所示。

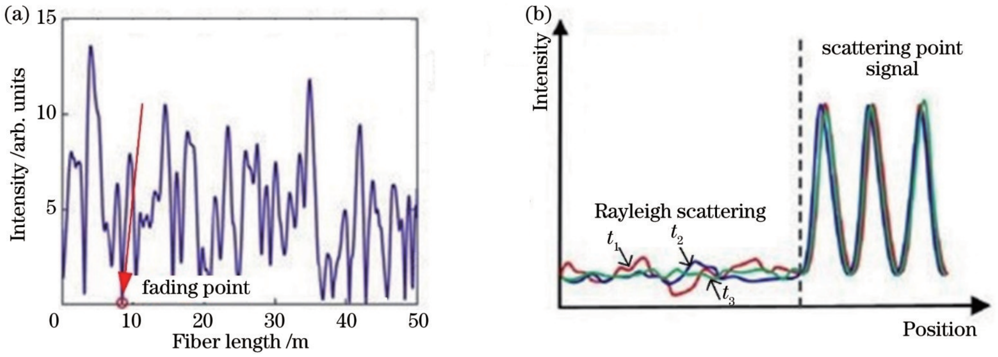


图 1　后向散射信号。(a)相干衰落现象；(b)散射增强信号与瑞利散射信号的对比

Fig. 1　Backscattering signal. (a) Coherent fading phenomenon; (b) comparison of scattering enhancement signal and Rayleigh scattering signal

相比于随机的瑞利散射点，散射增强微结构点的散射中心分布在光纤中固定位置，其散射强度可人为控制，第m个微结构点的强度和相位[6]可分别表示为

$$A_m^2 = k^2 A\frac{d}{W}, \tag{5}$$

$$\psi_m = \sum_{j=1}^{m}\frac{4\pi d}{\lambda}n, \tag{6}$$

式中：k为散射增强微结构点相对于瑞利散射点的增强倍数。如图 1(b)所示，散射增强微结构点的散射信号与瑞利散射相比具有更高的强度及稳定性。相比于瑞利散射，散射增强微结构点可以有效抑制相干衰落，大幅提高系统的信噪比和测量精度，对高精度 DAS 应用具有重要的意义。

2.2　散射增强微结构光纤制备技术

通过粒子掺杂或者激光改性技术可实现光纤后向散射增强。粒子掺杂技术在光纤制备过程中通过在光纤中掺杂硼、锗等氧化物可显著提升后向散射光信号信噪比[7-8]，但掺杂光纤的制备工艺复杂且成品光纤传输损耗大，难以实现大量应用。加拿大拉瓦尔大学研究人员为了解决掺杂光纤传输损耗大的问题，提出了一种钙基纳米粒子掺杂散射增强传感光纤[9]，实现了光纤瑞利散射的可调，并将掺杂光纤传感长度提升至百米量级。激光改性技术主要分为紫外激光辐射[10]和飞秒激光刻蚀[5]，前者基于光纤材料对紫外光的光敏性，光纤材料在紫外曝光的过程中折射率发生改变；后者通过高峰值功率的飞秒脉冲激光在聚焦区引起光纤强烈的非线性吸收，从而带来永久的折射率调制。飞秒激光刻蚀技术具有无须剥离涂覆层、耐超高温等特点，但是其复杂制备工艺和微结构点传输损耗较大等因素限制了其在大容量光纤传感网中的应用。现如今，散射增强光纤制备的主要技术是紫外激光辐射，通过刻写超弱光纤光栅(UWFBG)阵列或刻写无色弱反射点阵列实现。

拉丝塔在线刻栅技术是典型的散射增强微结构光纤制备技术。常规光纤的丙烯酸酯涂层对紫外激光有强吸收，这是限制紫外激光对纤芯进行折射率调制的关键因素。1993 年，英国南安普敦大学研究团队[11]提出拉丝塔在线刻栅技术，在光纤拉丝后、进入涂覆装置前，使用 KrF 准分子激光对光纤进行单脉冲曝光，将 UWFBG 写入光纤中，这种方式既实现了光纤散射增强微结构写入，又保证了光纤的力学性能。因其在制备大批量光栅阵列方面具备巨大优势，拉丝塔在线刻栅技术得以快速发展，目前德国光子技术研究所[12]和德国 FBGS 公司[13]已经实现了 UWFBG 阵列的商业生

产并将其应用于DAS中。武汉理工大学研究团队在UWFBG阵列研究方面取得不错的成果。该团队[14]在拉丝塔在线刻栅技术中融入更加稳定的基于相位掩模板的刻栅工艺，制备出的大容量光栅阵列具有良好的波长、反射率一致性，其制备系统、结果如图2(a)～(c)所示；2022年，该团队[15]利用该技术连续制备了54 km的散射增强微结构光纤，实现了长距离分布式声波传感。

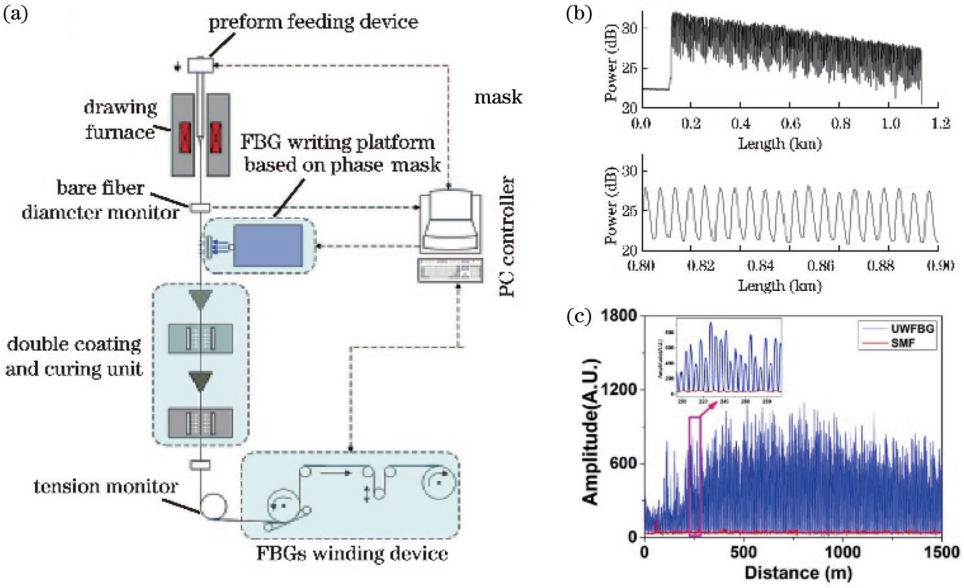


图2 散射增强微结构光纤制备。(a)拉丝塔在线刻栅技术制备系统图[14]；(b)UWFBG阵列的OTDR迹线图[14]；(c)散射增强光纤与普通单模光纤信号对比图[16]

Fig. 2 Fabrication process of scattering enhanced microstructure fiber. (a) Drawing of online grating technology preparation system for wire drawing tower[14]; (b) OTDR trace map of UWFBG array[14]; (c) comparison of signals of scattering enhanced fiber and ordinary single mode fiber[16]

从光纤涂层新材料的技术路线出发，2017年，美国OFS公司[17]提出了基于透紫外涂层光纤的在线刻栅技术，通过使用透紫外涂层光纤、基于相位掩模板的紫外刻栅技术以及卷对卷自动走纤系统，实现了km级散射增强微结构传感光纤制备。2021年，华中科技大学研究团队[18]研发出匹配商用拉丝塔工艺的透紫外光纤涂层并拉制出透紫外涂层光纤，其紫外激光透过率可达79%，传输损耗约为0.21 dB/km，且力学性能与普通单模光纤一致。基于此光纤，该团对利用微结构传感光纤精密制造系统制备了离散散射增强传感光纤[2]和连续散射增强传感光纤[19]，将其分别应用于DAS系统和光频域反射仪(OFDR)系统中，其制备系统及制备结果如图3(a)～(c)所示。通过程控式全息干涉波长控制技术，该研究团队连续制备了具有20个波长的波分复用、时分复用混合编码型光栅阵列[20]，结合激光光束整形和控制，可以实现任意波长、反射率编码控制[21]，如图3(d)～(e)所示。相比于拉丝塔在线刻栅技术，该技术不仅具备大容量制备优势，还具备微结构点质量精密可控、光纤长度和光栅复用灵活以及成本更低等优点。

通过在光纤中刻写无色弱反射点阵列实现散射增强也被应用于DAS中。该方案在紫外刻栅方案基础上去除了相位掩模板，直接通过紫外光曝光在光纤中引入局部折射率改变。如图4(a)、(b)所示，华中科技大学团队[22]基于该技术制备了5 m间隔、15 dB散射增强的微结构光纤，其带宽覆盖了整个放大自发辐射(ASE)谱宽。该技术方案制备的无色弱反射点没有波长选择性，相比于窄带的UWFBG，可避免温度和应变带来的增大带宽偏移的影响。

3 基于离散散射增强微结构光纤的分布式声波传感技术

3.1 DAS传感原理

光纤DAS是通过测量由光纤轴向应变的改变引起的光相位变化实现声波感知的[23]，其传感原理分为感知和定位两部分。声波作用在光纤上，会使光纤在轴向产生应变，从而改变光纤中瑞利散射信号的相位。DAS通过监测后向瑞利散射光的相位变化，得到光纤的轴向应变变化，最终实现声波和振动的定量感知。此外，由于不同位置的瑞利散射光可通过其反射回光纤发射端的时间进行区分，因此根据到达时间可以实现不同位置的声波传感。近年来，有多种基于上述原理的DAS相位解调方案被提出，包括外差相干探测方案[24]、基于3×3耦合器的相位解调方案[25]、相位生成载波(PGC)方案[26]、基于线性扫频脉冲的相位解调方案[27]等，它们都能实现分布式的声波探测。

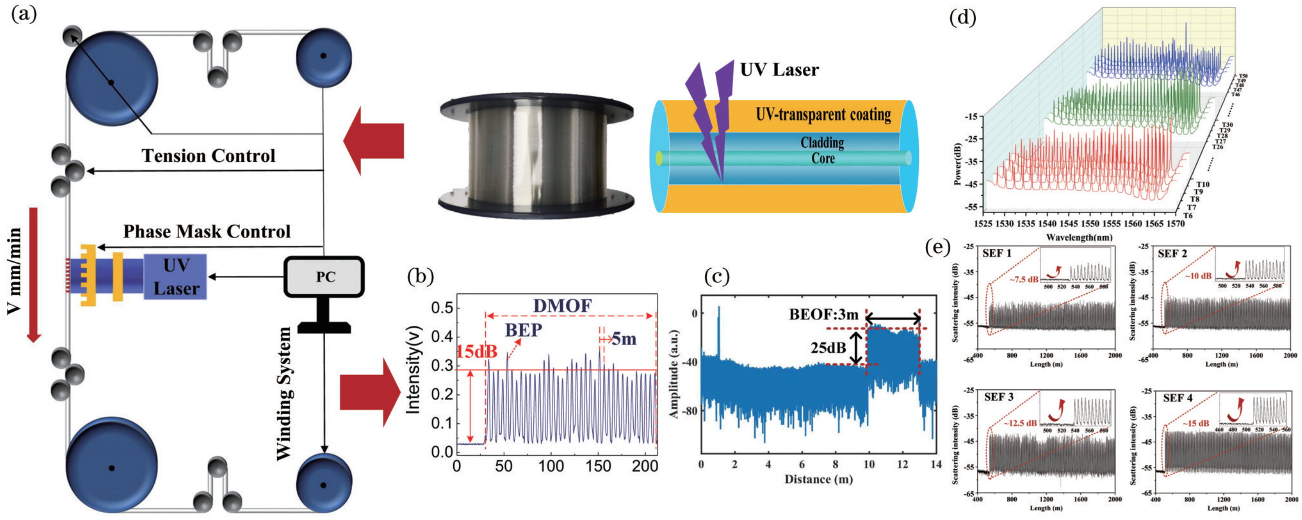


图 3 透紫外涂层光纤在线制备及结果。(a)基于透紫外涂层光纤的在线刻栅技术[18];(b)离散散射增强光纤[12];(c)连续散射增强光纤[19];(d)混合编码型光栅阵列光谱[20];(e)梯度散射增强光纤后向散射曲线[21]

Fig. 3 UV-transparent fiber on-line fabrication and its results. (a) Online grating technology based on UV coated optical fibers[18]; (b) discrete scattering enhanced fiber[12]; (c) continuous scattering enhanced fiber[19]; (d) hybrid encoding grating array spectra[20]; (e) gradient scattering enhanced fiber spectra[21]

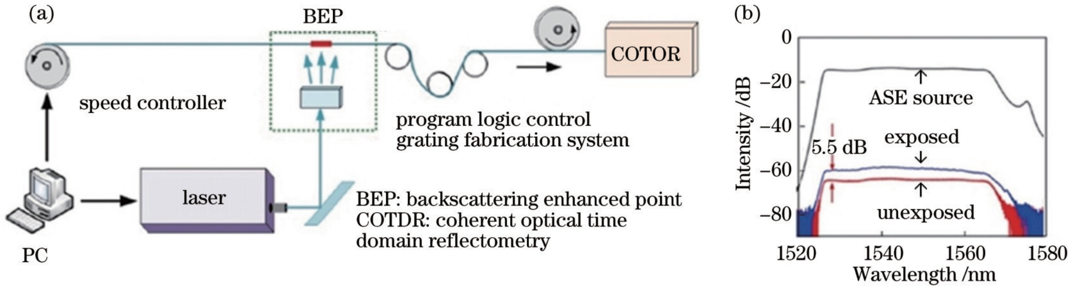


图 4 无色弱反射点制备及其结果。(a)无色弱反射点制备系统图;(b)制备前后光纤后向散射光信号对比

Fig. 4 Colorless weak reflection point fabrication and its result. (a) Colorless weak reflection point preparation system diagram; (b) comparison of fiber backscattered light signals before and after preparation

3.2 离散散射增强微结构光纤声波传感技术

对于单模光纤的DAS技术,脉冲内干涉带来信噪比低、干涉衰落、信号一致性差等局限性[4]。离散散射增强微结构光纤通过在光纤纵向引入一系列的散射增强点实现高质量声波传感,具体来说,其包括抑制脉冲内干涉和提升散射强度两个方面。散射增强点的散射强度远大于瑞利散射的强度,在后向散射中散射增强点的散射占主导地位,使得后向散射光的来源不再是脉冲内瑞利散射信号的干涉,从而从根本上杜绝了随机散射导致的干涉衰落、信号一致性差的问题。同时,散射增强光纤散射强度的大幅提升也进一步提升了信噪比。

基于离散散射增强光纤的特点,研究人员对DAS进行针对性的改进,从低频相位漂移补偿[28-29]、分辨率提升[30-31]、系统响应带宽拓宽[32-33]、探测距离增大[21, 34]等多个维度提升DAS系统性能,其代表性方案如图 5和表 1所示。

3.3 分布式声压增敏光缆传感技术

尽管散射增强光纤可以提升后向散射光强,但这并不会提高其对声波探测的灵敏度。普通单模光纤声波探测的灵敏度很低,约为 −207.76 dB re:1 rad/(μPa·m)[35],很难直接用于声波探测。目前,声波探测光纤的增敏技术主要包括二次涂覆增敏技术、准分布式增敏技术、全分布式增敏技术,也有相关研究使用以上技术来提升散射增强光纤的声波探测能力。

二次涂覆增敏技术通过在光纤成缆前在表面涂覆一层声压敏感材料来提高光纤的声波探测灵敏度。1979 年,McMahon 等[36]和 Hocker[37]就已分别分析了二次涂覆增敏理论,并分别提出了三层理论增敏模型(光纤层、一次涂覆层、二次涂覆层)和二层理论增敏模型(光纤和一次涂覆层为第一层,二次涂覆层为第二层),之后其便被应用于普通单模光纤增敏。2017 年,Lavrov 等[38]将 3.5 mm 的 RTV655 材料涂覆在 7 个光栅间距为 1.5 m 的弱光纤光栅(WFBG)表面,并在外层包裹增强聚合物纤维和热塑塑料,制备出了直径小

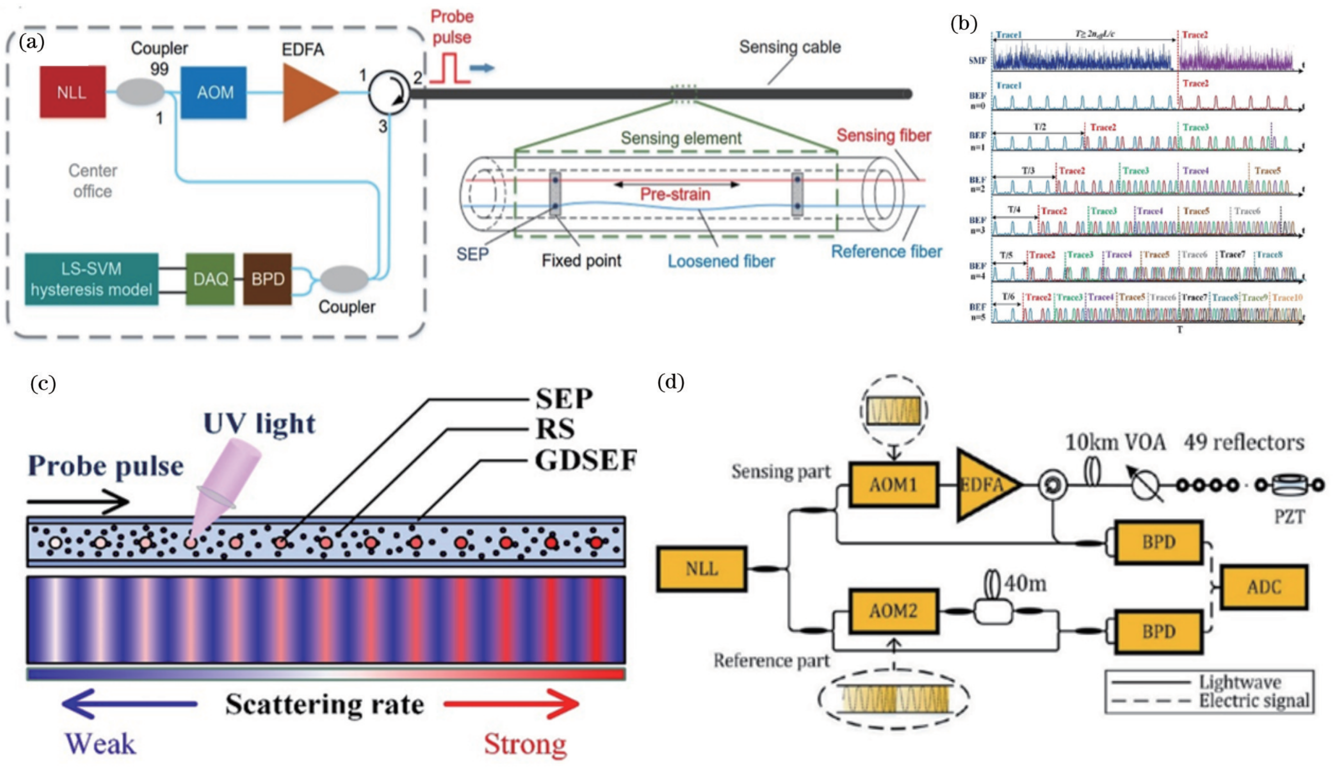


图 5　典型基于散射增强光纤的 DAS 性能提升方案。(a)低频漂移补偿方案[29]；(b)系统响应频带拓宽方案[33]；(c)探测距离增大方案[21]；(d)空间分辨率提升方案[30]

Fig. 5　Typical DAS performance improvement scheme based on scattering enhanced fiber. (a) Low frequency drift compensation scheme[29]; (b) frequency response band expansion scheme[33]; (c) detection distance expansion scheme[21]; (d) spatial resolution improving scheme[30]

表 1　基于散射增强光纤的 DAS 性能提升探索

Table 1　Exploration of improving DAS performance based on scattering enhanced fiber

Performance	Scheme	Institution	Ref. No
Compensation of low-frequency phase drift	Auxiliary interferometer	Shanghai Jiao Tong University	[28]
	Reference fiber compensation＋temperature hysteresis compensation	Huazhong University of Science and Technology	[29]
Spatial resolution improvement	Pulse linear sweeping	Shanghai Jiao Tong University	[30]
	Pulse coding	University of Electronic Science and Technology of China	[31]
Frequency response expansion	Frequency multiplexing	Nanjing University	[32]
	Time-slot multiplexing	Huazhong University of Science and Technology	[33]
Detection distance increase	End scattering enhancement	University of Southampton	[34]
	Gradient scattering enhancement	Huazhong University of Science and Technology	[21]

于 20 mm、总长为 60 m 的六元柔性水听器阵列，其声压灵敏度可达－143.7 dB re：1 rad/μPa@40 Hz。2020 年，庞彦东[39]采用聚醚聚氨酯对 WFBG 阵列光纤进行二次涂覆，制备出了直径为 0.9 mm、光栅间距为 50 m 的光纤水听器阵列，其在 200～2000 Hz 频带范围内均有增敏效果，但声压灵敏度响应不平坦。2021 年，丁朋等[40-41]在 Hocker 提出的二层理论模型基础上建立了二次涂覆 WFBG 阵列光纤的三层理论模型，并制备出了直径为 0.4 mm、光栅间距为 50 m 的高密度聚乙烯涂覆的光纤水听器阵列，如图 6 所示，其声压灵敏度在 5～10 Hz 频率范围内的响应起伏为 6.7 dB，综合灵敏度提升约 40 dB，但波形保真度较差。

准分布式增敏技术最早被应用于干涉式光纤水听器增敏，通过将光纤依次缠绕在水听器骨架上来提高

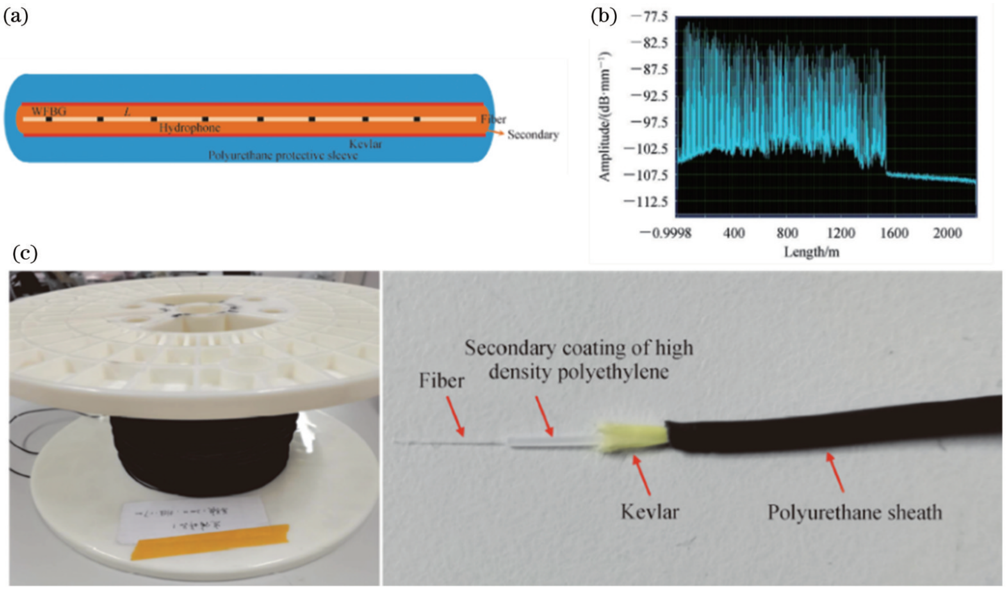


图 6 二次涂覆 WFBG 阵列光纤光缆[41]。(a)WFBG 阵列光纤示意图；(b)WFBG 阵列光纤时域反射光强；(c)WFBG 阵列光纤实物图

Fig. 6 Secondary coated WFBG array fiber optic cable[41]. (a) Schematic diagram of WFBG array fiber; (b) time domain reflected light intensity of WFBG array fiber; (c) physical image of WFBG array fiber

光纤的声波探测灵敏度，增敏效果与弹性体材料尺寸、传感光纤线圈长度和线圈绕制工艺有关。多个增敏基元串接形成的声波探测阵列一般为准分布式传感阵列，且在成缆应用时，往往需要对光缆内部进行充油或充胶以排尽内部空气并实现零浮力。2019 年，郭振等[42]使用多波长布拉格光栅(FBG)阵列光纤，通过准分布式增敏技术制备出了外径为 20 mm 的 32 元光纤水听器阵列，水听器单元的平均声压灵敏度可提升至 −143.9 dB re：1 rad/μPa@20～2000 Hz，且频率响应波动小于 3 dB。2020 年，Li 等[12]使用 5 m 间隔的后向散射增强光纤，通过准分布式增敏技术实现了声压灵敏度最高可达的 −83.7 dB re：1 rad/μPa@80 Hz 的准分布式探测网络，其结构如图 7 所示。2022 年，Li 等[43]使用 20 m 间隔的 WFBG 阵列光纤设计了一种直径为 20 mm、长为 0.75 m 的高灵敏水听器单元，其平均声压灵敏度可提升至 −113 dB re：1 rad/μPa@10～1000 Hz，且频率响应波动小于 3 dB。2023 年，Fang 等[44]使用 60 m 间隔的散射增强光纤设计了一种基元声压灵敏度高达 −101.21 dB re：1 rad/μPa@100～3000 Hz 的准分布式光学麦克风探测阵列，频率响应

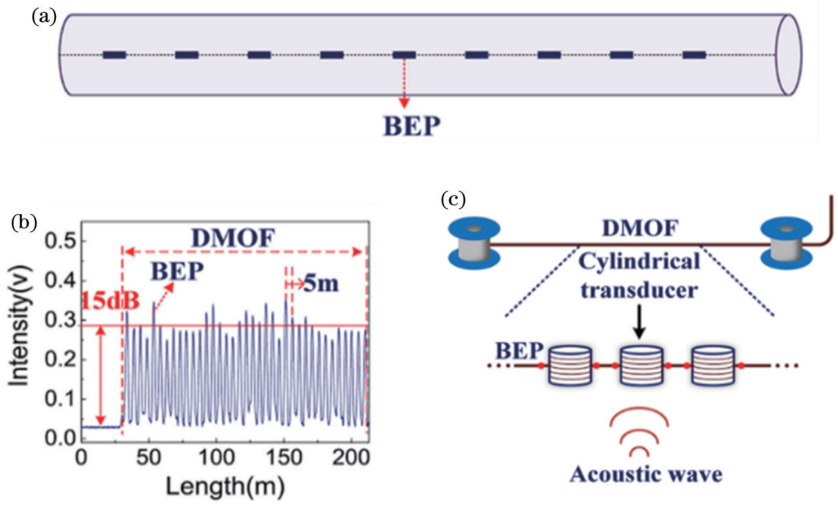


图 7 后向散射增强光纤准分布式增敏阵列[12]。(a)后向散射增强光纤示意图；(b)后向散射增强光纤的后向散射光强；(c)阵列示意图

Fig. 7 Backscatter enhanced fiber quasi distributed sensitization array[12]. (a) Schematic diagram of backscatter enhanced fiber; (b) backscatter intensity of backscatter enhanced fiber; (c) array diagram

波动小于3 dB，并将该光纤应用于无人机声学探测与定位。

全分布式增敏技术通过将光纤缠绕在连续增敏缆芯上来实现全分布声压增敏。2021年，Chen等[45-46]使用5 m间隔的后向散射增强光纤以5∶1的缠绕比制备出了一种外径为24 mm的全分布式增敏光缆，示意图如图8所示，其平均声压灵敏度可达−137 dB re：1 rad/μPa@5~2000 Hz，频率响应波动约为4 dB。此外，该增敏光缆低频响应优异，最高可达−125.3 dB re：1 rad/(μPa·m)@1 Hz，具有良好的信号保真度。

以上应用于散射增强光纤的三种增敏技术对比如表2所示，其中准分布式增敏技术和全分布式增敏技术原理一致，仅在成缆时存在差异。

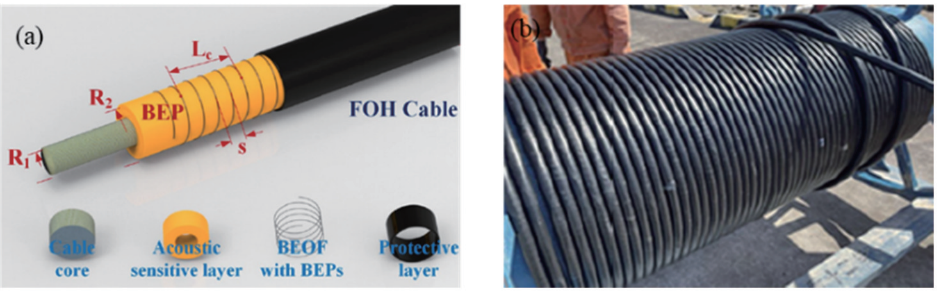


图8　全分布式增敏光缆[46]。(a)示意图；(b)实物图

Fig. 8　Fully distributed sensitization optical cable[46]. (a) Schematic diagram; (b) physical image

表2　应用于散射增强光纤的三种增敏技术对比表

Table 2　Comparison of three sensitization enhanced technologies for scattering enhanced fiber

Sensitization enhanced technology	Sensitivity	Diameter	Maximum cable length	Frequency response flatness	Fully distributed detection
Secondary coating sensitization	Moderate	Ultra-thin	Maximum sensing distance of the system	Relatively poor	Yes
Quasi-distributed sensitization	High	Moderate	Related to the length of the elementary winding coil and the elementary spacing	Good	Yes
Fully distributed sensitization	High	Moderate	Maximum sensing distance/winding ratio	Good	Yes

3.4　分布式声波传感技术典型应用

一些特殊应用领域要求传感器采集密度高、传输容量大、探测距离长、灵敏度高，以及定位准确，如：石油管道安全监测要求检测范围广，无盲区探测；地震勘探技术要求数据采集系统具有高灵敏度、高空间分辨率、低成本、部署灵活的特点。随着基于微结构散射增强光纤DAS系统的不断完善与发展，研究者们已开展了其在多个工程领域的应用探索。这些应用主要包括管道监测[47-50]、声源目标探测[44,46,51]、结构健康探测[52-55]以及地质资源勘探[56-60]。目前，已有的研究进展以及应用效果如表3所示。其中，分布式声波增敏光缆的相关应用在近年来备受关注，通过设计特殊增敏结构来提高其对环境声波的感知能力，已被广泛应用于分布式水听器、声场识别定位中。2020年以来，华中科技大学研究团队将自研的散射增强分布式增敏光缆应用于分布式水下和低空声学目标探测，例如：2021年该团队设计了一款高灵敏的声敏光缆，灵敏度可达−127 dB re：1 rad/μPa；2022年该团队基于该声敏光缆设计了一种1 m小道距海洋地震勘探拖缆，并进行了海试，获得了高分辨的海底地质图像[51]；2023年该团队使用该声敏光缆实现了海洋安全应用，成功实现对水面船只、水下小型航行器和蛙人的精准探测[45]；同年，该团队使用该声敏光缆进行了长时间、大范围的潮汐监测，有望为未来潮汐大范围连续监测提供一种新方法[61]；同年，该团队使用声敏光缆实现了低空无人机探测与高精度定位，定位误差在0.5 m以内，实现了低空声学目标的轨迹追踪[44]。

4　基于连续散射增强微结构光纤的分布式应变传感技术

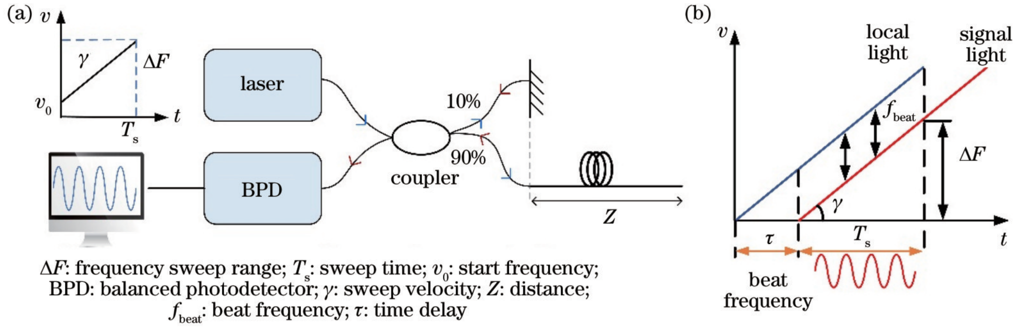
4.1　光频域反射仪传感原理

光频域反射仪(OFDR)于1981年由Eickhoff等[62]提出，其基本原理与微波领域中调频连续波技术类似。OFDR的基本结构和传感原理如图9所示。OFDR采用线性扫频的连续可调谐激光器作为光源，光源发出的光经耦合器分为两路，一路进入参考光路并被反射回耦合器中作为参考光，另一路进入传感光路中，其中后向瑞利散射光(RBS)也被返回到耦合器中，此时传感光和参考光发生拍频干涉后产生拍频信号并被探测器捕捉到。具体的OFDR传感原理如图9(b)所示，对

表 3　分布式声波传感技术典型应用进展

Table 3　Typical application progress of distributed acoustic sensing technology

Field	Monitoring parameter	Year	Overview of research	Ref. No
Pipeline monitoring	Corrosion defect	2020	Defect identification accuracy exceeds 94%	[47]
	Pipeline flow rate	2020	High precision detection of pipeline flow through scattering enhanced optical fibers	[48]
	External invasion	2022	Recognition accuracy of external rupture events in complex environments is greater than 85%	[49]
	Leakage identification	2023	Leakage with a small scale of 0.5 mm can be monitored through scattering enhanced optical fibers	[50]
Target detection	Unmanned aerial vehicle	2023	Enhanced fiber optic acoustic sensors (FOASs) are used to detect UAV, with a measurement sensitivity of −101.21 re: 1 rad/μPa	[44]
	Marine seismic survey	2022	Fully continuous fiber optic sensitized streamer with sensitivity of −137 dB re: 1 rad/(μPa•m)	[51]
	Underwater target	2023	Distributed sensitizing cable sound pressure sensitivity of −137.2 dB re: 1 rad/(μPa•m)	[46]
Structural health monitoring	Track defects	2022	Multiple defects can be successfully identify and locate along the railway line, with a standard deviation of 0.314 m	[52]
	Tunnel safety	2021	Tunnel reinforcement steel ring structure monitoring, recognition rate is larger than 97.8%	[53]
	Building intrusion	2022	Scattering enhanced optical fiber is used for intrusion detection around facilities, with a detect distances of >100 feet	[54]
	Extreme environment	2021	Femtosecond laser engraved optical fiber, extreme temperature sensing (1000 ℃)	[55]
Geological resource exploration	Oil exploration	2021	Recording direct and reflected seismic waves in a vertical well with microstructure optical fibers	[56]
	VSP	2019	Clear and high signal-to-noise ratio VSP waveform is obtained	[57]
	Fault exploration	2020	Deep imaging of stratigraphic data can detect the intersection fault of two underground boreholes	[58]
	Oil well temperature measurement	2020	High-temperature resistant scattering enhanced optical fiber is developed, with extra 1 year lifespan at 150 ℃	[59]
	Subsea oil field	2020	Enhanced Rayleigh scattering cable to obtain multi well data for image coverage	[60]



ΔF: frequency sweep range; T_s: sweep time; v_0: start frequency; BPD: balanced photodetector; γ: sweep velocity; Z: distance; f_{beat}: beat frequency; τ: time delay

图 9　OFDR的基本结构和传感原理

Fig. 9　Basic structure and sensing principle of OFDR

于传感光路中的某一位置点Z，其对应的传感光与参考光之间的时延差为τ_z，经过拍频干涉后，位置Z处对应的拍频频率$f_{\text{beat}}=\gamma\tau_z=2\gamma nZ/c$，其中$\gamma$表示可调谐激光器的调谐速度，$n$是光纤的有效折射率，$c$是光在真空中的传输速度。

OFDR技术利用相干检测技术将传感光纤中每一点的位置信息转化为拍频信号的频率变化，再通过傅里叶变换解调拍频变化以表征传感光纤的沿线位置-

幅值信息，从而实现对光纤的损耗和断点检测。OFDR具有高空间分辨率和高信噪比的测量优势，可广泛用于光纤链路诊断、分布式应变/形变检测以及高密度散射增强光纤的分布式应变解调。

4.2 高密度散射增强光纤应变传感技术

OFDR分布式应变测量的原理是通过检测瑞利散射光谱偏移量来实现对应变信息的解调。基于传感光纤中各位置的相位信息提取瑞利散射光谱信息，建立波长漂移量与应变之间的线性对应关系，并通过对应变变化前后的参考组和测量组信号做互相关运算，从而实现对应变信息的分布式解调。对于OFDR传感技术，其空间分辨率、测量灵敏度、准确度以及探测范围主要依赖于瑞利散射光谱信息的质量。然而，对于普通单模光纤(SMF)，其瑞利后向散射信号(RBS)强度通常很弱，这大大降低了瑞利散射光谱的信噪比，继而影响了应变测量下的互相关相似度判断，从而导致SMF难以满足OFDR应变测量系统对更高传感分辨率和更大检测范围的要求。因此，可通过设计高密度散射增强光纤来直接提高RBS强度，从而改善OFDR系统的应变传感性能。

目前，高密度散射增强光纤主要通过纤芯掺杂、改变光纤微结构等方法来提升RBS强度，继而改善分布式应变传感系统的信噪比，最终扩大应变探测范围。研究者们已设计了多种制备方法，主要包括纤芯掺杂技术、布拉格光栅刻写技术以及高数值孔径光子晶体光纤技术等。其中，纤芯掺杂技术主要通过提高纤芯非均匀性来提高RBS强度，但其制造过程比较复杂，这大大增加了系统成本。2018年，韩国标准科学研究院[63]将掺Ge光子晶体光纤应用到OFDR系统中，在空间分辨率为5 cm且弯曲半径为1 mm的情况下，测得掺Ge光子晶体光纤的应变灵敏度为0.138 GHz/με[图10(a)]。布拉格光栅刻写技术利用相位掩模板，通过紫外曝光在单模光纤上连续刻写布拉格光栅，从而提高光纤的整体瑞利散射强度。2022年，深圳大学王义平团队[64]通过连续紫外曝光SMF使得RBS提升了37.3 dB，并实现了分布式应变解调，空间分辨率达到2 mm且探测范围为200～2600 με[图10(b)]。类似地，华中科技大学孙琪真团队[19]在透紫外涂层光纤上连续刻写了栅区长度为9 mm、间隔为1 mm的高密度散射增强光纤，使得RBS提升了25 dB，同时实现了400 μm的空间分辨率和4400 με的应变探测范围[图10(c)]。然而，由于连续布拉格光栅的带宽和刻写范围有限，只有当入射波长在光栅波长刻写范围内，光纤才有明显的散射增强范围。

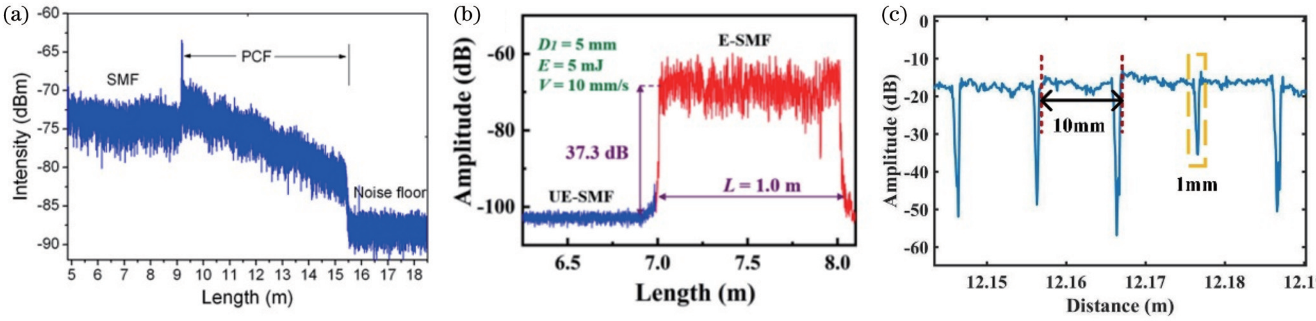


图10 高密度散射增强光纤。(a)掺Ge光子晶体光纤[63]；(b)连续曝光单模光纤[64]；(c)紫外曝光透紫外涂层光纤[19]

Fig. 10 High density scattering enhanced fiber. (a) Ge doped photonic crystal fiber[63]; (b) continuously exposed single mode fiber[64]; (c) UV exposed transparent UV coated fiber[19]

4.3 散射增强多路光纤形变传感技术

光纤形状传感是一种新型的形状测量技术，其可直接测量光纤本身或与之紧密相连的待测物体的姿态、位置、形状等三维空间信息。光纤形状传感器通常由多个具有空间对称分布特性的光纤/纤芯组成，首先利用多根纤芯之间的差分应变响应来获得形状传感器的形状参数，然后通过结合形状重构模型如弗莱纳框架[65]、平行传输框架[66]等重建出光纤形状传感器的三维形状。对于光纤形状传感器，均可通过紫外曝光或者飞秒激光刻写的方式来刻写光栅阵列，通过提高光纤的RBS强度提高形状传感器的信噪比，从而提高应变测量准确度并最终提高形状重构精度。

光纤传感器根据设计方式可分为两类，即多芯光纤和自封装式传感器。多芯光纤只有一个包层和涂覆层，但是有多个纤芯。其中一个芯位于中心位置，其他芯则在圆周上以约几十微米的等间隔平行分布[67]。2007年，LUNA公司[68]首次利用刻栅的多芯光纤结合OFDR进行形状和位置测量，如图11(a)所示，当使用5 mm光栅栅区、间隔为1 cm的FBG阵列时实现了2.2%的测量准确度。2012年，美国NASA兰利研究中心的Moore等[65]对刻有光纤光栅阵列的多芯光纤的形状进行重构，得到的最大重构误差为测量长度的7.2%。这种光纤由于多芯光纤尺寸小，弯曲半径小，适合狭窄且对一致性要求高的领域。与多芯光纤相比，自封装式传感器可由多根单模光纤或散射增强光纤组成，将裸光纤粘在基材上或直接粘在一起，形成光纤簇。自封装式传感器具有直径大、测量灵敏度高等特点，适合大弯曲半径的场合。2017年，加拿大蒙特

利尔理工学院研究人员[69]将三根紫外曝光后的散射增强光纤粘在一起形成光纤簇，其结构如图11(b)所示，该结构将形状重构误差控制在1 mm以下。类似地，2019年Beisenova等[70]采用平行式多路氧化镁微粒掺杂光纤实现了40 dB的瑞利散射信号增强，并利用OFDR系统实现了形状测量。

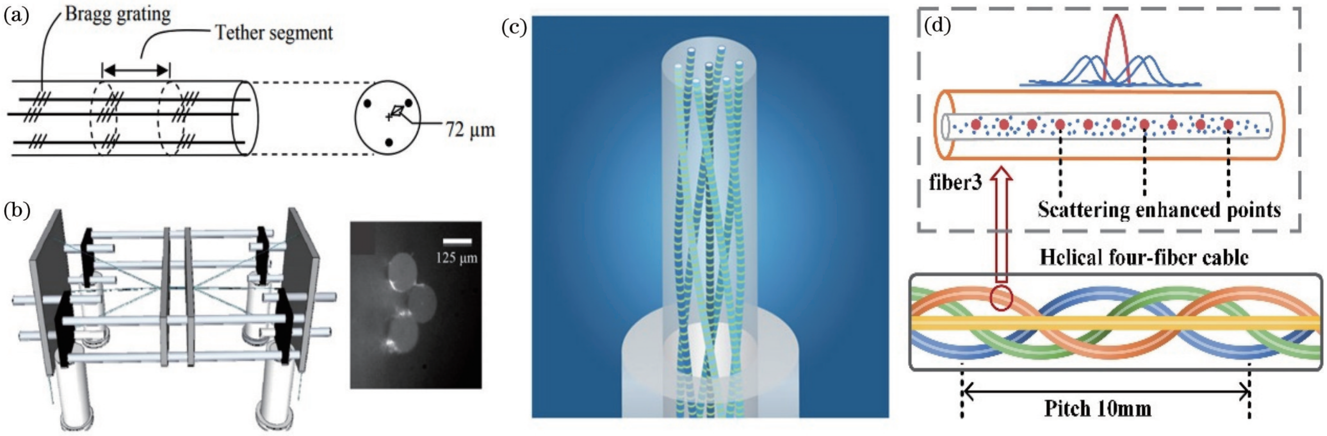


图11　形状传感光纤。(a)刻写布拉格光栅的平行式多芯光纤[68]；(b)散射增强光纤平行式光纤簇[69]；(c)刻写布拉格光栅的螺旋式多芯光纤[72]；(d)散射增强光纤螺旋式光纤簇[73]

Fig. 11　Shape sensing fiber. (a) Parallel multi-core fiber with engraved Bragg grating[68]; (b) scattering enhanced fiber parallel fiber cluster[69]; (c) spiral multi-core fiber with engraved Bragg grating[72]; (d) spiral fiber cluster of scattering enhanced fiber[73]

形状传感器在实际形状测量过程中不仅会发生弯曲，还会因为运动而出现旋转、扭曲问题，扭曲将导致形状感知的准确性和稳定性受到影响，并最终导致形状重建的失败。基于此，可通过将螺旋结构应用到自封装式传感器或者多芯光纤中，同时检测形状传感器的弯曲和扭转特性，从而进一步优化形状传感器的应变测量准确性和重构精准度。通过将螺旋结构与散射增强技术相结合，在提高传感信号信噪比的同时能够实现对扭转信息的检测，进而改善三维重构结果。例如，OFS公司[71]利用紫外光及相位掩模板在螺旋多芯光纤上刻写连续光纤光栅以实现三维重构。2019年，俄罗斯科学院自动化和机电研究所研究人员[72]采用近红外飞秒脉冲激光在螺旋多芯光纤上刻写了光栅，如图11(c)所示。多芯光纤的尺寸小，多为几十微米，导致在螺旋多芯光纤上刻写光栅的难度大大提高，因此也可采用将多根散射增强光纤螺旋缠绕成自封装式传感器来完成形状重构。2022年，华中科技大学研究人员[73]利用多根散射增强螺旋缠绕式多纤光缆提高了应变测量的空间分辨率和准确度，同时测得了弯曲和扭转应变，在200 mm的形状传感器上实现了0.29%的高精度三维形状重构，如图11(d)所示。

4.4　分布式应变/形变传感技术典型应用

近年来，OFDR凭借其高分辨、高灵敏、大动态范围和高精度测量的优势，已广泛应用于应变、形变监测系统。基于OFDR技术和散射增强光纤的特点已经发展了一些较为新颖的应用，表4总结了几种典型的应用案例，如结构健康监测(主要包括飞行器的机翼应变检测、建筑物的裂纹判断和船舶的横向应变场变化监测)和三维形状测量(主要应用在医疗微创介入手术中，实现对导管位置的实时高精度追迹)。

表4　分布式应变/形变传感技术典型应用

Table 4　Typical applications of distributed strain/deformation sensing technology

Application scenario	Specific application	Institution	Ref. No
Structural health monitoring	Distributed strain detection of commercial aircraft wings	LUNA company	[74]
	Distributed monitoring helicopter blade deflection	Japan Aerospace Exploration Agency	[75]
	High-density distributed crack tip sensing and monitoring	Wuhan University of Technology	[76]
	Strain field monitoring system in ship transverse under hydrostatic	Wuhan University of Technology	[77]
Shape sensing	Shape sensing-assisted epi-dural needle guidance	Nazarbayev University	[78]
	Medical catheter position tracking	Intuitive company	[79]
	Shape reconstruction of medical catheters	University of Leuven	[80]

5 总结与展望

分布式光纤传感技术具有高分辨、高灵敏、全分布的优势，在日益增长的需求牵引与研究者们的共同努力下，已经逐渐迈向工程化。常用普通单模光纤存在传感信噪比较低、光强度衰落、测量一致性差、测量精度受限等问题，同时存在传感距离、响应带宽与信噪比相互限制等问题，基于散射增强特种光纤的分布式传感系统可有效解决上述问题。本文重点分析了散射增强微结构传感光纤的散射特性及噪声抑制机理，阐述了散射增强光纤的类型与精密制备技术，总结了基于散射增强微结构传感光纤的DAS与OFDR系统的性能改进技术，论述了DAS信噪比与灵敏度增强机理及其典型应用；阐述了散射增强水听复合缆的研究进展，介绍了高灵敏分布式水听器系统的构建及其水听应用；综述了高密度光栅散射增强微结构光纤，基于光频域反射计实现高分辨、高灵敏、高可靠全分布式应变传感；设计散射增强微结构螺旋多芯光纤，结合高可靠重构算法实现高精度三维形状传感并进行实际应用。

展望未来，仍可从多方面对基于散射增强光纤的分布式传感技术进行改进和拓展应用研究，如散射增强微结构光纤的材料和结构等参数优化设计、高效率高稳定光刻制备工艺的进一步改进、光纤散射增强特性辅以智能AI算法以优化传感解调精度、高精度三维形状感知与散射增强光纤分布式水听器的交叉拓展应用。相信未来随着散射增强特种传感光纤的进一步发展，基于散射增强光纤的分布式传感系统将在大部分领域凸显不可替代的作用。

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Research Progress in Scattering Enhanced Microstructured Fiber and Its Distributed Sensing Technology

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Abstract

Significance Information technology is the cornerstone that supports the development and social life of today's world, with its important component of sensing technology. Fiber optic sensing technology utilizes light waves as information carriers and transmission media to achieve the collection and measurement of signals in the environment. As an important branch of fiber optic sensing technology, distributed fiber optic sensing can achieve long-distance, high-resolution, and highly sensitive continuous distributed detection, obtaining two-dimensional spatio-temporal distribution information. Compared to the other two types of scattering distributed sensing, the system based on Rayleigh scattering features higher backscattering power and faster response and is more suitable for detecting dynamic and static signals such as sound waves and strain. With the increasing demands for engineering applications such as resource exploration, structural health monitoring, and underwater exploration, distributed fiber optic sensing has developed rapidly in recent years.

At present, most distributed sensing systems usually employ single-mode fiber (SMF) as the sensing medium. However, its Rayleigh backscattering signals are extremely weak, resulting in poor signal-to-noise ratio (SNR) of sensing light, which in turn causes poor SNR of demodulation signals in distributed sensing systems. Additionally, the intensity fading effect induced by high laser coherence can cause sensing blind spots, and the light intensity fading can also result in poor sensing consistency among multi-channels. Meanwhile, due to the influence of optical transmission loss, the sensing SNR of ordinary non-amplification SMF optic systems is limited at long distances. The fully continuous characteristics of backscattering signals in optical SMFs can also result in mutual limitations between the system response bandwidth and sensing distance. Therefore, scattering enhanced special optical fibers are introduced into distributed sensing systems based on Rayleigh scattering. By continuously changing the fiber material and structure, or introducing discrete scattering enhancement mechanisms, the distributed sensing limitations of ordinary optical SMFs are overcome in specific sensing parameters, sensing performance, and other aspects.

Thus, in some specific application scenarios that require high-precision detection, scattering enhanced optical fiber has irreplaceable advantages. In recent years, numerous research institutions and researchers have conducted research on scattering enhanced fiber optical distributed sensing systems and obtain significant results.

Progress We focus on analyzing the scattering characteristics and noise suppression mechanisms of scattering enhanced microstructured sensing fibers, and elaborate on the types and precision preparation techniques of scattering enhanced fibers. Meanwhile, the performance improvement techniques of DAS and OFDR systems based on scattering enhanced microstructured fiber are summarized (Fig. 5 and Table 1), and the mechanism and typical applications of DAS SNR and sensitivity enhancement are discussed. The research progress of scattering enhanced hydrophone composite cables is elaborated (Table 2), and the construction of highly sensitive distributed hydrophone systems and their hydrophone applications are introduced (Table 3). Additionally, we summarize the high-density grating scattering enhanced microstructured fiber to achieve high-resolution, highly sensitive, and highly reliable fully distributed strain sensing based on optical frequency domain reflectometry (Figs. 10 and 11). Combined with highly reliable reconstruction algorithms, scattering enhanced microstructured spiral multi-core optical fibers are designed to achieve high-precision three-dimensional shape sensing and practical applications (Table 4).

Conclusions and Prospects In summary, we study the mechanism of distributed sensing efficiency enhancement from the perspective of scattering enhanced special optical fibers, introduce the automatic precision fully continuous writing technology, and focus on the principles of its optical time domain and optical frequency domain distributed sensing systems. Meanwhile, the research progress of distributed acoustic sensing and optical frequency domain reflection technology based on scattering enhanced microstructured fiber is summarized, and typical engineering applications based on the above two systems are summarized.

In the future, distributed sensing technology based on scattering enhanced optical fibers can still be improved and expanded in various aspects. For example, the material and structural parameters of scattering enhanced microstructured fiber can be optimized, and the high-efficiency and stable writing preparation process can be improved. Additionally, the scattering enhancement characteristics of optical fibers can be combined with intelligent AI algorithms to optimize sensing demodulation accuracy. Meanwhile, the high precision 3D shape sensing and scattering enhanced fiber distributed hydrophone can be further extended to various cross applications. As the scattering enhanced special sensing fibers further develop in the future, distributed sensing systems based on scattering enhanced fibers will play an irreplaceable role in most fields.

Key words sensors; distributed fiber optic sensing; scattering enhanced fiber; distributed acoustic sensing; optical frequency domain reflectometry