

激光与光电子学进展

集成马赫-曾德尔干涉大量程高灵敏度压力传感器

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摘要 提出了一种基于非对称马赫-曾德尔干涉 (AMZI) 和 3D 打印立体光刻树脂模块的大量程压力传感器, 分析了传感器的特性, 推导的公式表明传感器的灵敏度与单臂长度成正比, 与衍射阶数成反比。在设计中, 高灵敏度通过小的衍射级实现, AMZI 压力传感器采用平面光波技术制造, 压力块采用树脂 (DM11) 3D 打印, 测试灵敏度为 0.3047 nm/MPa。

关键词 马赫-曾德尔干涉; 压力传感器; 大范围; 高灵敏度; 集成光学

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Large Range and High-Sensitivity Pressure Sensor Based on Integrated Mach-Zehnder Interference

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Abstract We present a large range pressure sensor based on asymmetric Mach-Zehnder interference (AMZI) and a three-dimensional (3D) printed stereolithography resin module. The filtering characteristic is analyzed, and formulas show that the sensor's sensitivity is proportional to the length of one arm and inversely proportional to the diffraction order. In our design, high sensitivity is realized by a small diffraction order. The AMZI pressure sensor is fabricated using planar lightwave technology, and the pressure block is 3D printed with resin (DM11). The measured sensitivity is 0.3047 nm/MPa.

Key words Mach-Zehnder interference; pressure sensor; large range; high sensitivity; integrated optics

1 引言

目前, 基于光学原理的传感器大量应用于各个行业, 例如折射率变化测量^[1]、医学测量^[2]、海洋探测^[3]等。其中压力传感器在水深勘探^[4-9]、油气井压力检测^[6-12]等领域应用广泛。光学传感器可分为非集成式和集成式^[4]。关于非集成大量程压力传感器的研究很多^[5-7, 10-16]。基于集成光学的压力传感器大多关注小范围和高灵敏度, 其测量范围小于 2 MPa^[17-30]。文献^[8]使用阵列波导光栅 (AWG) 测量了高达 40 MPa 的高压, 但其与非集成传感器相比, 分辨率并不高。为了提高灵敏度, AWG 芯片装配了 3D 打印相位放大压力块。分辨率提高到 0.6 kPa, 动态范围增加到 80 MPa^[9]。这使得集成光学在大范围压力传感器的研究中跟上了非集成器件的水平。从技术角度看, 非集成式的传感器

都是单个制作, 其品质与操作员的水平直接相关, 而集成光波导器件则利用半导体工艺, 用光刻、干法刻蚀等工艺一次性制作出几百个完全一样的器件。大规模量产的成本低, 并且品控稳定, 因此基于集成工艺的大量程高灵敏度压力传感器具有广阔的市场前景。

提出了一种高灵敏度大量程压力传感器。该传感器基于非对称马赫-曾德尔干涉 (AMZI)。大多数关于马赫-曾德尔干涉 (MZI) 或 AMZI 的研究使用单波光光源, 通过观察输出光强度来确定测量的压力^[17-20, 22-24]。一些研究使用 AMZI 的峰值波长来确定要测量的物理量^[23, 31-33], 本设计采用第 2 种方法。在设计中气体或液体的压力通过 3D 打印压力块传输到芯片, 测试灵敏度为 0.3047 nm/MPa, 该传感器实际测量量程达到了 110 MPa, 实现了大量程高灵敏度的压力测量。

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2 原理

AMZI 压力传感器结构如图 1 所示。在此结构中,只有短臂的一部分被压缩,第 m 阶的波长 λ 为

$$\frac{2\pi}{\lambda} \cdot l_2 \cdot n_e - \frac{2\pi}{\lambda} [(l_1 - l_w) n_e + l_w n_e] = 2\pi \cdot m, \quad (1)$$

式中: n_e 为波导的有效折射率; m 为衍射级; l_1 为传感器短臂长; l_2 为传感器长臂长; l_w 为传感器短臂受压感应区域长。

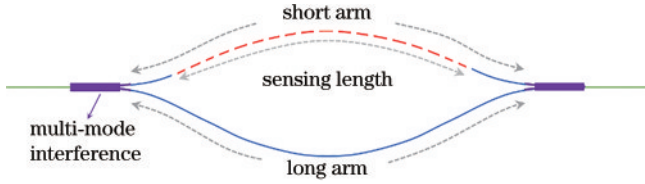


图 1 AMZI 传感器结构图

Fig. 1 Structure diagram of AMZI sensor

通过式(1)可以推断出:

$$l_2 \cdot n_e - [(l_1 - l_w) n_e + l_w n_e] = m \cdot \lambda. \quad (2)$$

当图 1 中虚线所示的波导有效折射率变化 Δn 时,峰值波长的变化为 $\Delta \lambda$,二者满足:

$$l_2 \cdot n_e - [(l_1 - l_w) n_e + l_w (n_e + \Delta n)] = m \cdot (\lambda + \Delta \lambda), \quad (3)$$

需要注意的是,式(3)中假设微小波长变化时波导的有效折射率 n_e 保持不变,此假设对低折射率差的波导材料(如本设计使用的 SiO_2 波导)是适用的,但对高折射率差的波导材料(如 Silicon-on-insulator(SOI))不适用。式(2)减去式(3)得

$$S = \Delta \lambda / \Delta n = l_w / m, \quad (4)$$

式中: S 为传感器的灵敏度。很明显,AMZI 的灵敏度与 l_w 成正比,与 m 成反比。

在设计 AMZI 压力传感器时,首先需确定 m 。较小的 m 有助于提高灵敏度。但考虑到光源的光谱宽度, m 不能太小。当没有压力时,中心峰值波长 λ_0 为

$$\Delta L \cdot n_e = m \cdot \lambda_0, \quad (5)$$

式中: $\Delta L = l_2 - l_1$ 为两臂的长度差。对应于 $m-1$ 的峰值波长为

$$\Delta L \cdot n_e = (m-1) \cdot (\lambda_0 + f_{\text{FSR}}), \quad (6)$$

式中: f_{FSR} 为自由光谱范围。通过式(5)、式(6)得

$$m = \lambda_0 / f_{\text{FSR}} + 1, \quad (7)$$

半导体工艺中的误差会导致峰值波长漂移。令 f_{FSR} 小于光源的光谱宽度有助于忽略工艺误差的影响。在实验中,光源的光谱宽度为 1525~1575 nm,因此最终选定 $m \geq 1550/50 + 1 = 32$ 。

文献[34]中讨论了干涉臂的设计原理。使用正弦作为线型。 l_1 、 l_2 的长度用 C++ 的线积分计算,压力块如图 2 所示,接触区域设计为扇形,以提高轴承极限。接触区域内波导的长度 l_w 由 Solidworks 计算。AMZI 芯片由 2 个相同的压力块夹紧,这是为了获得更高的压力上限^[5]。压力块中部的扇形形状抬升,以在特定区域内向芯片施加压力,如图 3 所示。

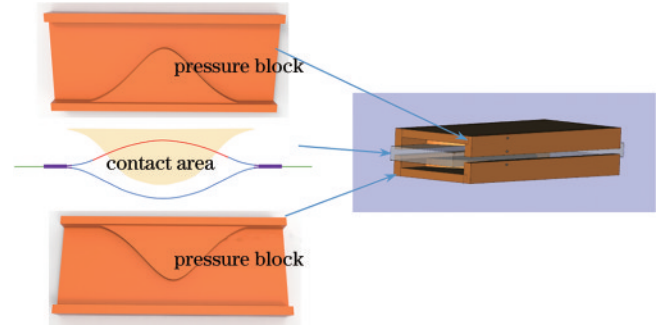


图 2 3D 打印压力块与 AMZI 的装配示意图

Fig. 2 Assembly diagram of 3D printing pressure block and AMZI

AMZI 的参数,如表 1 所示,利用 Comsol 计算波导的有效折射率。所用的光源宽度为 50 nm。根据式(7),该器件在此范围内将有 3 个峰值。输出光强度 P_{out} 由 MZI 的标准函数计算:

$$P_{\text{out}}(\lambda) = \frac{1}{2} \left\{ 1 + \cos \left[\frac{2\pi}{\lambda} (\Delta L \cdot n_e - l_w \cdot \Delta n) \right] \right\}. \quad (11)$$

通过计算得到 AMZI 压力传感器输出光谱,如图 4 所示,理论计算的器件灵敏度为 0.32 nm/MPa,如图 5 所示。在本次计算中,使用了文献[9]中的数据,即受压波导的有效折射率变化为 1.571×10^{-5} /MPa。

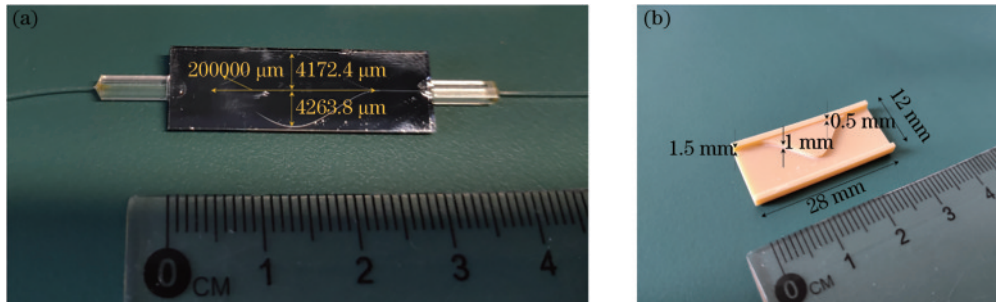


图 3 细节尺寸。(a) AMZI 芯片; (b) 3D 打印压力块

Fig. 3 Detail dimensions. (a) AMZI chip; (b) 3D printed pressure block

表 1 AMZI 参数

Table 1 AMZI parameters

Parameter	Value
l_w /mm	12
Contact area /mm ²	63.9
m	78
ΔL / μm	82.68
l_1 / μm	22000.00
l_2 / μm	22082.68
Waveguide cross-section /($\mu\text{m} \times \mu\text{m}$)	4 \times 4
Core/cladding index	1.47459/1.4448
n_c (@1550 nm)	1.4622
MMI length / μm	519.80
MMI width / μm	30.00

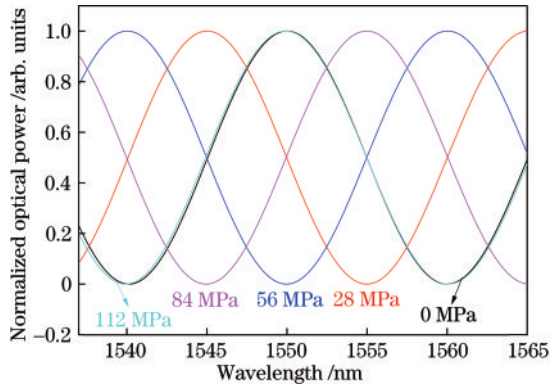


图 4 AMZI 压力传感器输出光谱理论计算图

Fig. 4 Theoretical calculation diagram of output spectra of AMZI pressure sensor

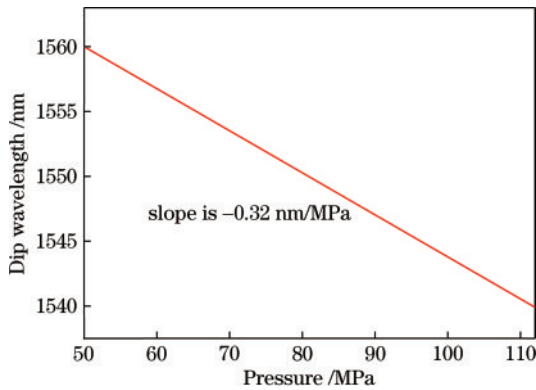


图 5 AMZI 压力传感器计算灵敏度

Fig. 5 Calculation sensitivity of AMZI pressure sensor

3 实验结果与讨论

AMZI 压力传感器芯片采用标准平面光波导技术制造。波导尺寸为 $4 \mu\text{m}$, 使用成熟且廉价的接触式光刻刻蚀。用单模光纤和 3D 打印树脂压力块封装的 AMZI 芯片, 如图 6 所示 (3D 打印的树脂类型为 DM11)。

在实验中, 使用放大自发辐射 (ASE) C 波段光源 (Golight) 作为输入, 并将输出光、输入光谱分析仪 (横河 AQ6370D)。ASE 光源的光谱不是完全平坦的, 所

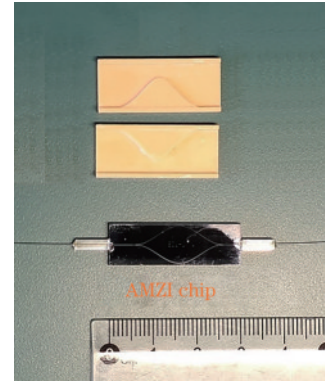


图 6 AMZI 压力传感器和 3D 打印压力块

Fig. 6 AMZI pressure sensor and 3D printed pressure block

以将 AMZI 的输出光谱除以光源的光谱, 归一化光谱就是器件在理想白光下的输出光谱, 测量系统如图 7 所示。施加在 AMZI 芯片上的压力根据悬臂长度、棱锥体顶部到旋转轴的距离、压力块和芯片之间的接触面积以及重量计算得出。

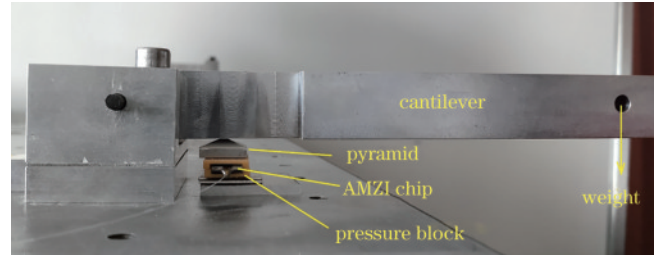


图 7 测量系统

Fig. 7 Measurement system

AMZI 压力传感器测试光谱如图 8 所示。由图 8 可知, 随着施加在传感器上的压力不断增大, 输出光谱在向短波方向移动, 当压力达到 110 MPa 时, 0 MPa 图像中右侧的波峰 1 移到了 1560 nm 附近, 也就是 0 MPa 时的波峰 0 位置, 在此情形下继续提高压力已无法分辨具体哪个峰在移动, 因此传感器的测量量程为 0~110 MPa。根据测量得出的传感器灵敏度如图 9 所示, 测量表明传感器灵敏度为 0.3047 nm/MPa , 实测

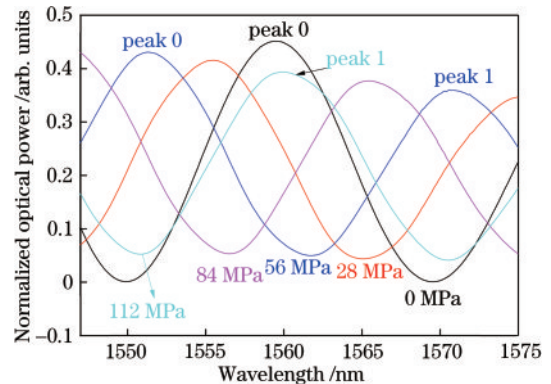


图 8 AMZI 压力传感器测试光谱图

Fig. 8 Test spectra of AMZI pressure sensor

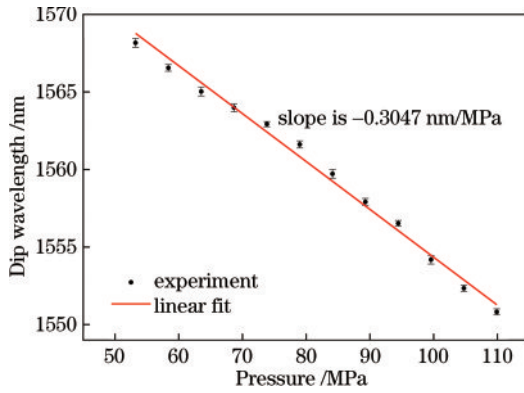


图9 AMZI压力传感器测试灵敏度

Fig. 9 Test sensitivity of AMZI pressure sensor

结果表明:本设计的传感器在光谱输出特征和灵敏度方面与理论计算相符合,实现了大量程、高灵敏度的压力测量。

考虑到使用的光谱仪的波长分辨率为 0.02 nm, AMZI 压力传感器的检测极限约为 0.0656 MPa,若使用更高波长分辨率的光谱仪可以进一步提高该检测极限。

本设计的压力块为 3D 打印的树脂 DM11。压力块从建模到打印只需几小时,对其承压部分(压力块中间的凸起形状)的尺寸进行修改即可调整传感器的灵敏度与量程。此外,打印一套压力块的成本不到十元,所提的这种方案不需要修改 AMZI 芯片。相比之下,采用调整 AMZI 设计的方法也可以调整传感器的灵敏度与量程,但从掩模板重新设计、制作到半导体工艺流程和封装完成至少需要 2~3 个月,整套流程的成本在 4~5 万元,对某特定量程传感器的需求数量较少(小于 100 个)的情况下,分摊成本较大。

表 2 基于不同技术路线的大量程光学压力传感器研究总结
Table 2 Summary of research on large range optical pressure sensors by different technical routes

Sensor	Measurement range /MPa	Integrated optics
Sensor in Ref. [10]	71	
Sensor in Ref. [11]	42	No
Sensor in Ref. [15]	7	
Sensor in Ref. [7]	10	
Sensor in Ref. [8]	40	
Sensor in Ref. [9]	80	Yes
This work	110	
SBE 911Plus (Seabird)	69	High end commercial products based on electrical principle

4 结 论

介绍了一种基于 SiO₂ 的 AMZI 和 3D 打印压力块

的集成光学大量程压力传感器,分析了 AMZI 的滤波特性,推导的公式表明 AMZI 的灵敏度与臂长成正比,与臂差成反比。AMZI 芯片采用标准平面光波导技术制造,3D 打印压力块的材料为 DM11,传感器的测量灵敏度为 0.3047 nm/MPa,压力测试范围可达 110 MPa。新型 AMZI 压力传感器适用于大范围压力测量,如海洋深度检测、油气井压力监测。所提的 AMZI 压力传感器需进行更多研究,其在高灵敏度、大量程测量方面很有前景。

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