

基于波长选择调制芯片的微波光子到达角测量(特邀)

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摘要 提出并实验验证了一种波长选择调制芯片的微波光子到达角(AOA)测量系统。该系统在绝缘体上铌酸锂平台上集成了类马赫-曾德尔干涉仪结构,通过两路平行的支路上级联微环谐振器与相位调制器,实现了波长选择以及信号独立调制。该方案利用光子下变频机制,将高频回波信号的相位差信息映射至低频信号的功率特征上,缓解了后端信号处理的带宽压力。实验结果表明,该系统能够有效测量 20、25、30 GHz 回波信号的相位差,在 $10^{\circ}\sim 170^{\circ}$ 范围内相位误差低于 $\pm 2.23^{\circ}$;基于相位差解算得到的 AOA,在半波长天线间距下 $0^{\circ}\sim 70.8^{\circ}$ 范围内得到的测量误差小于 $\pm 2.31^{\circ}$ 。

关键词 微波光子学; 到达角测量; 集成光子学; 绝缘体上铌酸锂; 微环谐振器

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1 引言

光子到达角(AOA)是表征无线信号传播方向的关键物理参数^[1],在雷达探测、通信、电子对抗以及卫星导航等领域具有至关重要的作用。精确获取 AOA 可支持高增益波束赋形、精确目标定位及高效同频干扰抑制^[2-5]。然而,随着电磁环境日趋复杂和应用场景日益多样,传统的电学测量方法受限于“电子瓶颈”,存在工作频率受限、工作带宽窄、抗干扰能力弱等局限性。微波光子技术凭借光子系统具备的大工作带宽、高速处理能力、低传输损耗及强抗电磁干扰等显著优势^[6],为高精度 AOA 测量提供了新的解决方案。

目前,基于微波光子的 AOA 测量方案主要可归纳为两类:功率-相位映射方案与时延估计方案。功率-相位映射方案通常利用光子辅助技术将空间天线接收到的回波信号的相位差信息转换为易于检测的光功率或电信号幅度^[7-10],其典型实现方式是将多路接收信号加载至调制器或多路调制系统,通过光学干涉将空间相位差映射为中频信号的幅度变化,再利用光功率计或电功率计监测这些参数,从而推算得到相应的相位差和 AOA 信息。时延估计方案则通过提取射频信号到达不同天线的时延差来解算 AOA^[11-13]。该方法通常利用光纤色散效应,将时延差异映射为频域的偏移或时间序列上的脉冲间隔,此类系统一般包含大规模的光子链路和光学空间链路。相较之下,功率-相位映射方案通常在系统复杂度、实时性及测量精度方面更具优势。然而,目前大多数功率-相位映射方

案仍基于分立器件构建,存在体积庞大、功耗高、稳定性有限等问题,难以满足机器人、无人机等应用场景对系统集成度和稳定性的苛刻要求。因此,微波光子 AOA 测量系统的集成化是突破当前技术瓶颈的重要途径。

近年来,随着绝缘体上铌酸锂(LNOI)^[14]、绝缘体上硅等集成工艺平台的日趋成熟,集成微波光子技术在器件集成度与系统功能复杂度方面取得了显著突破。在功能单元层面,微波光子滤波器^[15-16]、光电振荡器^[17-18]、波形产生器^[19]、波束成形网络^[20]等核心模块已相继实现片上集成;在此基础上,面向微波光子雷达^[21-22]、信道化接收^[23]、瞬时频率测量^[24]等应用的集成系统也陆续问世,标志着集成微波光子技术正从器件层面向系统层面延伸。上述研究成果不仅验证了集成微波光子领域的巨大潜力,也为探索 AOA 测量的集成方案提供了有益借鉴。

本文基于 LNOI 平台设计并实现了一种波长选择调制芯片,通过在类马赫-曾德尔干涉仪结构的两个平行臂上集成级联的微环谐振器(MRR)与相位调制器(PM),实现了片上波长选择和信号独立调制。基于该架构,已成功验证了多普勒测量^[25]、混频移相^[26]、AOA 测量^[27]等多种功能。本文聚焦于 AOA 测量应用,在前期工作^[27]的基础上,进一步优化实验设计,利用片上相干合路将空间相位差信息映射至下变频信号的功率分布,实现了 20~30 GHz 高频回波下的变频 AOA 探测。实验结果表明:该系统在 $10^{\circ}\sim 170^{\circ}$ 的相位差测量区间内,相位误差低于 $\pm 2.23^{\circ}$;在半波长天线

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间距下,解算得到的 AOA 在 $0^\circ \sim 70.8^\circ$ 范围内的测量误差小于 $\pm 2.31^\circ$ 。

2 基本原理

基于波长选择调制芯片的微波光子 AOA 测量系统如图 1 所示,该系统主要由光源、片上调制和光电转

换三个模块组成。片上调制模块采用类似马赫-曾德尔干涉仪的结构,在其两个平行的波导臂上集成了 MRR 和 PM。MRRs 用于实现波长选择,PMs 则用于对筛选后的光载波进行独立调制。光源模块需要提供至少两个不同波长的相干光,可通过外部调制技术、锁模光纤激光器或光学频率梳等方式实现。

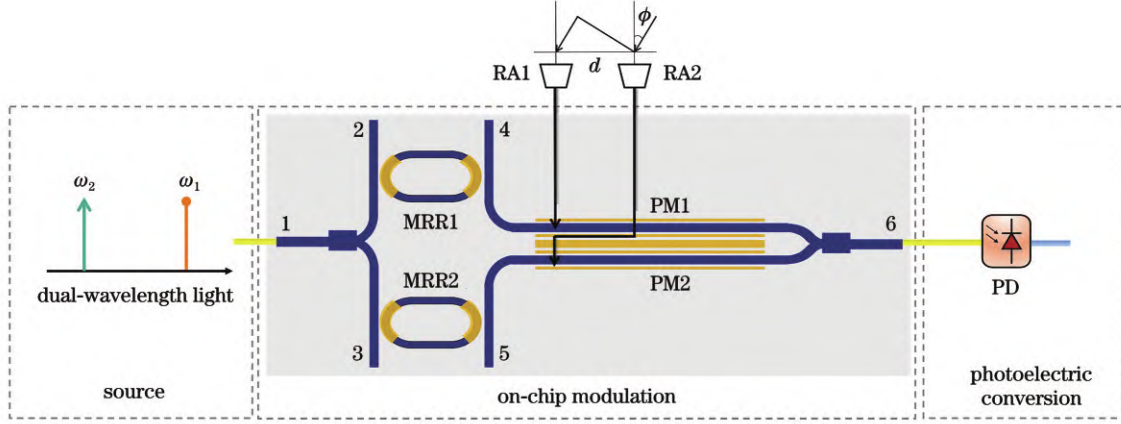


图 1 基于波长选择调制芯片的微波光子 AOA 测量系统示意图

Fig. 1 Schematic diagram of microwave photonic AOA measurement system based on a wavelength-selective modulation chip

本文采用由激光源(LD)和马赫-曾德尔调制器(MZM)构建的外调制技术生成双波长相干光。将中心频率为 ω_c 的激光输入 MZM,并在频率为 ω_0 的调制信号驱动下将其偏置于最小传输点,以实现载波抑制双边带(CS-DSB)调制。在小信号调制条件下,片上输入光场表达式可写为

$$E_{in}(t) = E_0 J_1(\gamma) (\exp(j\omega_1 t) + \exp(j\omega_2 t)) \quad (1)$$

式中: E_0 为 LD 的振幅; γ 为 MZM 的调制系数; $J_1(\gamma)$ 为自变量为 γ 的 1 阶第一类贝塞尔函数; ω_1 和 ω_2 分别对应调制的上下边带,其值分别为 $\omega_1 = \omega_c + \omega_0$ 、 $\omega_2 = \omega_c - \omega_0$ 。需要注意的是, ω_c 和 ω_0 的选择需要与 MRRs 的响应匹配。

$$E_{out}(t) = E_0 J_1(\gamma) \times (J_0(m) \exp(j\omega_1 t) + J_0(m) \exp(j\omega_2 t) + J_1(m) \exp(j(\omega_1 t + \omega_{RF} t + \varphi + \pi/2))) +$$

$$J_1(m) \exp(j(\omega_2 t + \omega_{RF} t + \pi/2)) - J_1(m) \exp(j(\omega_1 t - \omega_{RF} t - \varphi - \pi/2)) - J_1(m) \exp(j(\omega_2 t - \omega_{RF} t - \pi/2))) \quad (4)$$

式中: m 为 PMs 的调制系数, $m = \pi V_{RF}/V_\pi$, V_π 为 PMs 的半波电压; $J_0(m)$ 和 $J_1(m)$ 分别表示自变量为 m 的 0 阶和 1 阶第一类贝塞尔函数。

经光电探测器(PD)探测后输出的信号为

$$\begin{aligned} i_{out} \propto E_{out}(t) \cdot E_{out}^*(t) = & E_0^2 J_1^2(\gamma) \times (J_0^2(m) \cos((\omega_1 - \omega_2)t) + J_1^2(m) (\cos((\omega_1 - \omega_2)t + \varphi) + \\ & \cos((\omega_1 - \omega_2)t - \varphi)) + J_0(m) J_1(m) (\sin((\omega_1 - \omega_2 + \omega_{RF})t) - \\ & \sin((\omega_1 - \omega_2 + \omega_{RF})t + \varphi)) + J_0(m) J_1(m) (\sin((\omega_1 - \omega_2 - \omega_{RF})t) - \\ & \sin((\omega_1 - \omega_2 - \omega_{RF})t - \varphi)) + J_1^2(m) (\cos((\omega_1 - \omega_2 - 2\omega_{RF})t - \varphi) + \\ & \cos((\omega_1 - \omega_2 + 2\omega_{RF})t + \varphi)) + J_1^2(m) (\cos(2\omega_{RF}t) + \cos(2\omega_{RF}t + 2\varphi))) \end{aligned} \quad (5)$$

通过合理设置 ω_0 和 ω_{RF} , 可将回波信号频率 ω_{RF} 下变频至 $\omega_1 - \omega_2 - \omega_{RF}$, 从而有效降低后端数据处理压力。低频分量 $\omega_1 - \omega_2 - \omega_{RF}$ 对应的功率表达式为

在片上,光信号首先经 1×2 多模干涉仪(MMI)分为两路,随后由 MRR1 和 MRR2 分别对两个边带进行滤波处理,实现 ω_1 和 ω_2 的分离。两路光信号分别作为新的光载波输入 PM1 和 PM2,实现独立调制。将两个天线接收到的回波信号分别加载到 PM1 和 PM2 上,其表达式可写为

$$V_1 = V_{RF} \cos(\omega_{RF} t + \varphi) \quad (2)$$

$$V_2 = V_{RF} \cos(\omega_{RF} t) \quad (3)$$

式中: V_{RF} 、 ω_{RF} 为信号幅度和频率; φ 为两个回波信号的相对相位差。

两路调制光信号经 2×1 MMI 合路后的输出光场表达式可写为

$$P \propto \frac{1}{2} E_0^4 J_1^4(\gamma) J_0^2(m) J_1^2(m) \cdot (1 - \cos \varphi) \quad (6)$$

由式(6)可知, $\omega_1 - \omega_2 - \omega_{RF}$ 分量的功率是相对相位差 φ 的函数:当 φ 为 0° 时,理论上观测到的功率最

小;当 φ 为 $\pm 180^\circ$ 时,则可测得最大功率。

设两个天线的间距为 d ,系统工作波长为 λ ,回波信号的 AOA 为 ϕ ,则信号到达两个天线的波程差为 $d \sin \phi$,因此 φ 可表示为

$$\varphi = \frac{2\pi}{\lambda} d \sin \phi \quad (7)$$

根据式(7)可得信号的 AOA 为

$$\phi = \arcsin \frac{\lambda \varphi}{2\pi d} \quad (8)$$

由式(8)可知, ϕ 与 λ 和 d 有关,将 d 设为待测信号的半波长,可得

$$\phi = \arcsin \frac{\varphi}{\pi} \quad (9)$$

根据式(6),可通过 $\omega_1 - \omega_2 - \omega_{RF}$ 分量的电频谱功率推算出相位差信息,进而结合式(9)计算 AOA。需要注意的是,式(6)反映的是功率与相位差之间的比例关系,实际计算 AOA 时,需要对信号功率进行归一化处理:

$$P_n = \frac{P}{P_0} \quad (10)$$

式中: P_n 为归一化后的信号功率; P 为不同相位差处测得的信号功率; P_0 为相位差 $\varphi = \pm 180^\circ$ 时所对应的最

大功率,则 φ 与 P_n 之间的映射关系可表示为

$$\varphi = \arccos(1 - 2P_n) \quad (11)$$

将式(11)代入式(9),即可推算 AOA 的数值。

3 实验与讨论

3.1 芯片介绍

LNOI 平台具备优异的电光性能、强波导限制能力以及互补金属氧化物半导体(CMOS)工艺兼容等优势,是实现高效线性调制与高密度集成的理想平台^[26],因此本文基于该平台研制了 AOA 测量芯片。该芯片采用济南晶正电子科技有限公司提供的 X 切 LNOI 晶圆,并由南智光电研究所完成流片制备。芯片架构如图 2 所示,整体尺寸为 $11.3 \text{ mm} \times 2.3 \text{ mm}$,主要由多对 MMI 两路级联的 MRRs 及 PMs 组成。其中,MRR 采用跑道型结构设计,由半径为 $149.88 \mu\text{m}$ 的半圆弯曲波导和长度为 $51.6 \mu\text{m}$ 的直波导组成,MRR 与总线波导的耦合间隙为 400 nm ,总光学路径长度约为 $1045.45 \mu\text{m}$,且 MRRs 的耦合区集成了热调电极,通过电压调谐可改变其谐振波长。在光耦合方面,该芯片采用光栅耦合器与光纤阵列配合的垂直耦合方式实现光信号的输入与输出,各输入输出波导端口由数字 1~6 标识。

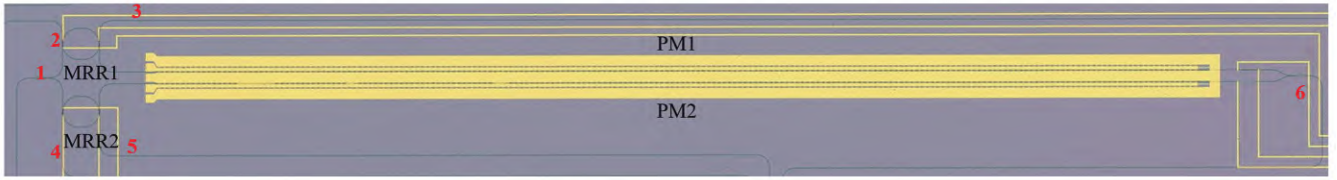


图 2 芯片显微镜照片

Fig. 2 Microscope image of the chip

3.2 实验结果

本文首先对 MRRs 的光谱响应进行测试。实验采用宽谱光源(ASE-CL-100-SM-B)作为输入光信号,通过光纤阵列与光栅耦合器垂直耦合进入芯片。实验中分别选取“端口 2 进-端口 3 出”与“端口 4 进-端口 5 出”的路径,利用光谱分析仪(YOKOGAWA AQ6370D)采集 MRR1 与 MRR2 下载端的传输光谱,实验结果如图 3 所示。测量结果表明,两路 MRRs 谐振峰之间的波长间隔 $\Delta\lambda$ 为 0.24 nm ,对应的频率间隔 Δf_{Δ} 约为 30 GHz ,MRR1 和 MRR2 的 3 dB 带宽分别约为 7 GHz 和 5 GHz 。

AOA 测量实验包含光载波调制、片上信号处理及低频信号检测三个环节。首先,可调谐激光器(IDPHOTONICS)产生的连续光经过偏振控制器(PC)调整后进入 MZM(Fujitsu FTM7938),并使其工作于 CS-DSB 状态。为使产生的 ± 1 阶边带能与 MRRs 的谐振峰对齐,从而筛选出高功率的新光载波并注入片中,将激光器的中心波长设置为 1550.3 nm ,

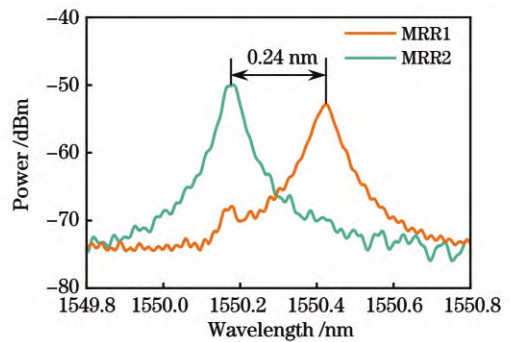


图 3 MRRs 的光谱传输曲线

Fig. 3 Optical transmission curves of MRRs

并将 ω_0 设定为两个 MRRs 谐振峰频率间隔的一半,即 15 GHz 。由光谱仪观测到的调制光谱如图 4(a)所示,载波抑制比约为 20 dB 。随后,该光信号经过 PC 调整并通过光纤阵列垂直耦合进入芯片,片上光信号由端口 1 进入,端口 6 输出的合路光谱如图 4(b)所示,此时的载波抑制比高达 48 dB 。最后,实验采用信号发生

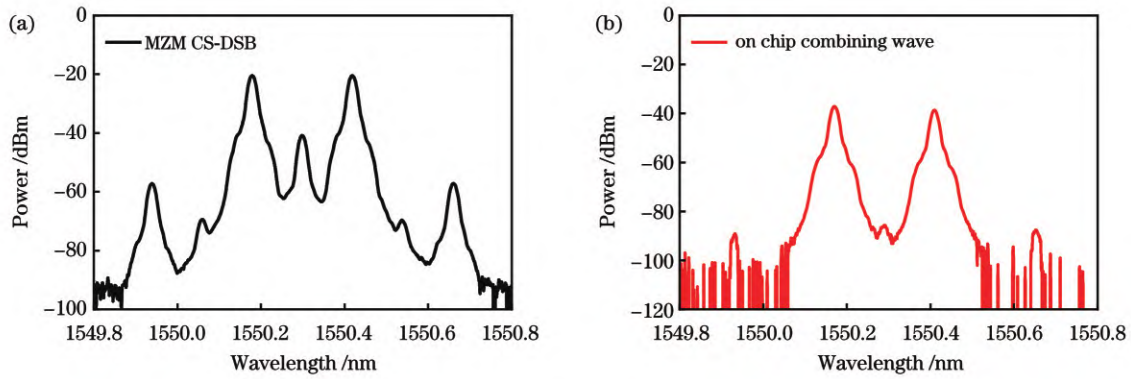


图 4 光谱测量结果。(a) MZM CS-DSB 光谱;(b)片上两路合波光谱

Fig. 4 Spectral measurement results. (a) Optical spectrum under MZM CS-DSB; (b) combined spectrum of two optical paths on chip

器(KEYSIGHT E8257D)发射频率 ω_{RF} 为 25 GHz 的信号用于模拟天线接收的回波信号,该信号经功分器分为两路:一路直接加载至下臂的 PM2 上,另一路经过移相器后加载至上臂的 PM1 上。通过精确调节移相器的相位,可模拟射频信号到达两个天线的相位差,从而等效改变待测 AOA。为了保证两路调制信号功率均衡,在其中一路增加了电衰减器。经 2×1 MMI 合束输出至片外的光信号,先经过掺铒光纤放大器(EDFA)放大以补偿链路损耗,最终由 PD 接收,并使用频谱分析仪(KEYSIGHT N9020B)进行信号观测。

频谱仪在 0~40 GHz 范围内观测到的所有拍频分量如图 5(a)所示,其中,频率分量 ω_0 由片上载波不完全抑制产生, ω_{RF} 分量源自两路信号幅度不对称性,结合 ω_0 和 ω_{RF} 的参数设置,下变频分量 $\omega_1 - \omega_2 - \omega_{\text{RF}}$ 为 5 GHz。该结果验证了系统将高频回波信号转换至低频的能力,从而构建了用于 AOA 测量的功率-相位映射关系,实现了低频探测。当调节移相器改变两路回波信号的相位差 φ 时, $\omega_1 - \omega_2 - \omega_{\text{RF}}$ 信号的功率随之变化,图 5(b)、(c)分别展示了 φ 为 0° 和 180° 时的输出频谱:当 φ 为 0° 时,信号淹没在噪声中;当 φ 为 180° 时,下变频信号功率最高,约为 -67.68 dBm。

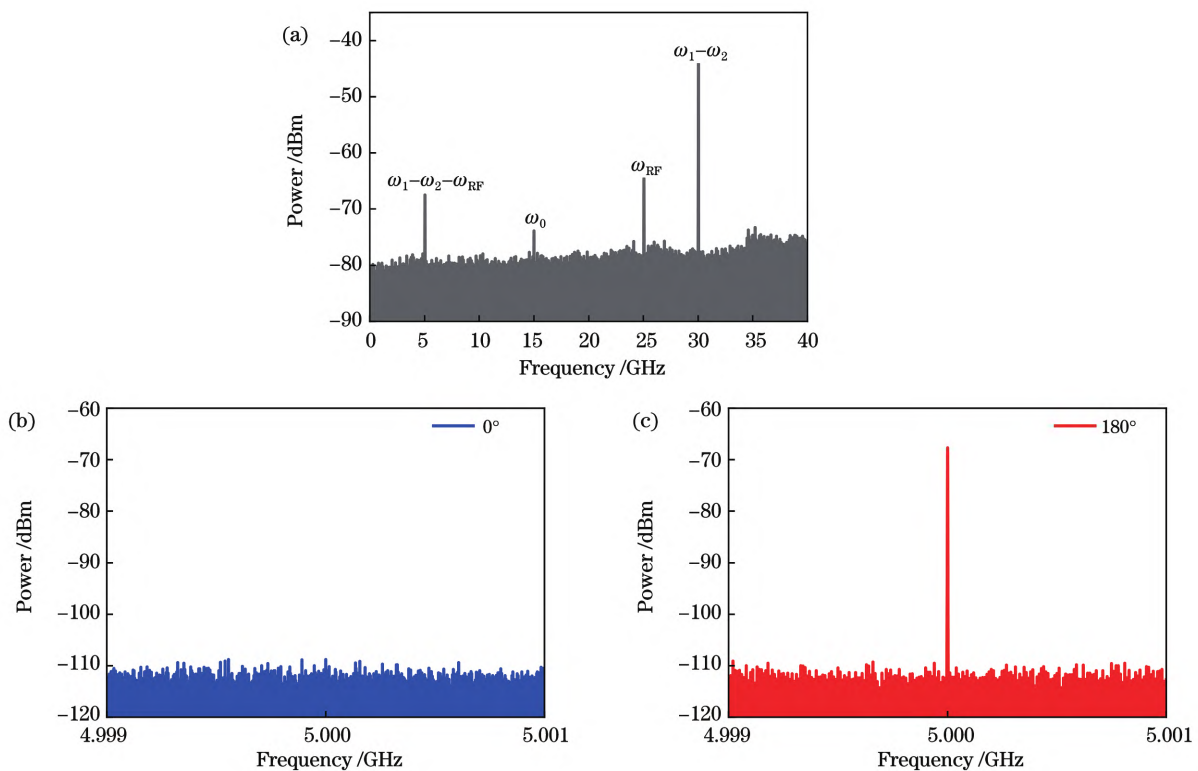
图 5 电谱图。(a) PD 转换后;(b)信号 $\omega_1 - \omega_2 - \omega_{\text{RF}}(0^\circ)$;(c)信号 $\omega_1 - \omega_2 - \omega_{\text{RF}}(180^\circ)$

Fig. 5 Electrical spectra. (a) After PD conversion; (b) signal $\omega_1 - \omega_2 - \omega_{\text{RF}}(0^\circ)$; (c) signal $\omega_1 - \omega_2 - \omega_{\text{RF}}(180^\circ)$

通过在 $-180^\circ \sim 180^\circ$ 范围内调节移相器并记录对应的电信号功率值,得到的功率-相位映射曲线如图 6 所示。由图 6(a)可知,实测的不同相位处归一化功率与式(11)定义的一类余弦偶函数模型吻合良好。由于该映射关系在相位差 φ 的 $\pm 180^\circ$ 测量范围内关于 0° 对称,这意味着根据功率值推算出的 φ 无法区分正负,即无法判断 AOA 的方向。为解决该问题,通常选择函数曲线的单调区间 ($-180^\circ \sim 0^\circ$ 或 $0^\circ \sim 180^\circ$) 进行测量,图 6(b)给出了在此区间内测量相位差与理论相位差

的误差曲线。结果表明,在 $0^\circ \sim 160^\circ$ 范围内测量误差较小,小于 $\pm 1.8^\circ$,而在 $160^\circ \sim 180^\circ$ 范围内误差相对较大,最大误差达 -5.5° 。这源于相位测量精度对功率灵敏度的依赖,对式(6)关于相位求一阶导,可得

$$\frac{dP}{d\varphi} \propto \frac{1}{2} E_0^4 V_{\text{RF}}^4 J_1^4(\gamma) J_0^2(m) J_1^2(m) \sin \varphi \quad (12)$$

当 φ 接近 180° 时, $\sin \varphi \approx 0$, 此时功率对相位的灵敏度趋于零,微小的功率波动将被转换为较大的相位抖动,从而导致该区域的相位恢复精度下降。

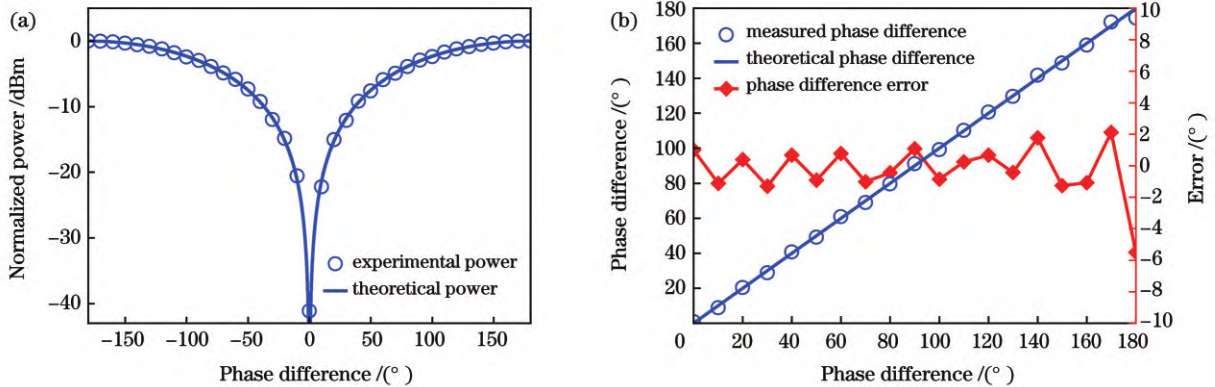


图 6 功率-相位映射曲线。(a) 实验功率与理论功率对比; (b) 实验相位差与理论相位差的误差

Fig. 6 Power-phase mapping curves. (a) Experimental power versus theoretical power; (b) error between experimental and theoretical phase differences

为扩展系统的工作带宽,可利用 MRRs 的 3 dB 带宽特性,通过设置 ω_0 灵活调节双波长的频率间隔 $\omega_1 - \omega_2$ 。将 ω_0 分别设置为 12.5 GHz 和 17.5 GHz,可实现 $\omega_1 - \omega_2$ 为 25 GHz 和 35 GHz,并相应设置回波信号 ω_{RF} 为 20 GHz 和 30 GHz。图 7(a)给出了三个频率下 $0^\circ \sim 180^\circ$ 范围内的相位差误差曲线,结果表明,该系统在 $10^\circ \sim 170^\circ$ 测量范围内,各频率回波信号的总体相位误差均小于 $\pm 2.23^\circ$,证明了该架构在宽带范围内具有良好的功率-相位映射一致性。将天线间距 d 设置为工作波长的一半时, $0^\circ \sim 180^\circ$ 的相位调谐范围对应 $0^\circ \sim 90^\circ$ 的 AOA 测量范围。图 7(b)给出了推算得到

的 AOA 测量误差曲线,误差在接近 90° 时显著增大,这与 φ 接近 180° 时功率-相位映射的灵敏度下降相关;若避开 180° 附近的相位误差区域, AOA 测量范围可达 $0^\circ \sim 70.8^\circ$, 整体误差在 $\pm 2.31^\circ$ 内。

此外,若进一步利用 MRRs 上集成的热调电极,通过电压调谐改变其有效折射率,可灵活调节两路 MRRs 的谐振峰频率间隔 $f_{\Delta\lambda}$ 。当外部光源采用光频梳时,光频梳技术与 MRRs 的可调谐特性相结合,有望在无需高频电本振的条件下进一步增大系统的工作带宽,从而支持更高频段回波信号的相位测量与 AOA 解算。

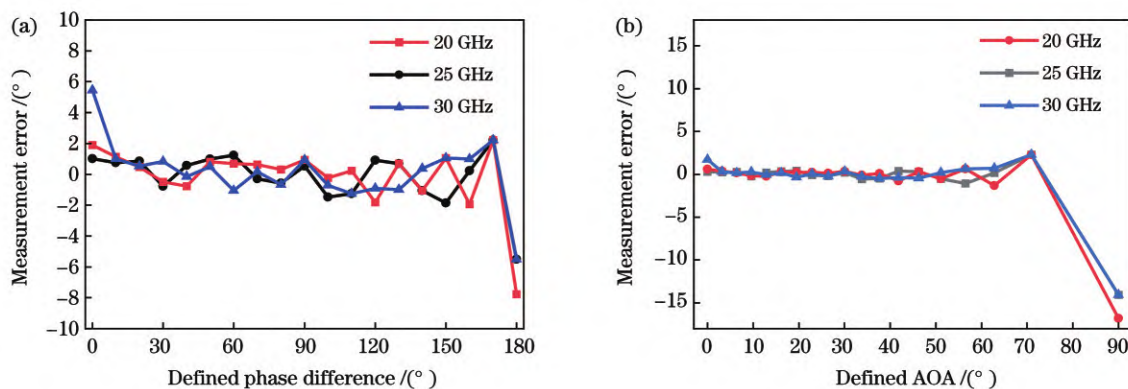


图 7 相位差和 AOA 测量误差。(a) 相位差测量值与理论值间的误差; (b) AOA 测量值与理论值间的误差

Fig. 7 Measurement errors of phase difference and AOA. (a) Error between measured and theoretical phase differences; (b) error between measured and theoretical AOA

在实际 AOA 测量系统中,由于天线方向图差异、通道增益不一致等原因,两个天线接收到的回波信号功率可能存在差异。为评估该非理想因素对系统测角精度的影响,本文开展了仿真研究。假设两个回波信号的振幅分别为 V_1 和 V_2 ,且 V_1 与 V_2 的比值为 $r(r < 1)$,则 PD 获得的信号 $\omega_1 - \omega_2 - \omega_{RF}$ 可以写为

$$i \propto J_0(m_1)J_1(m_2)\sin((\omega_1 - \omega_2 - \omega_{RF})t) - J_0(m_2)J_1(m_1)\sin((\omega_1 - \omega_2 - \omega_{RF})t - \varphi) \quad (13)$$

式中: $m_i = \pi V_i / V_\pi$ ($i = 1, 2$) 为 PM1 和 PM2 的调制系数; V_π 为 PMs 的半波电压; $J_0(m_i)$ 和 $J_1(m_i)$ 分别为相应自变量的 0 阶和 1 阶第一类贝塞尔函数。

该信号的功率表达式可以写为

$$P \propto A^2 + B^2 - 2AB \cos \varphi \quad (14)$$

式中: $A = J_0(m_1)J_1(m_2)$; $B = J_0(m_2)J_1(m_1)$ 。

当 φ 为 0° 和 180° 时,对应 $P \propto (A - B)^2$ 和 $P \propto (A + B)^2$,由于 $A \neq B$,该条件下架构的干涉对比

度下降,但功率-相位映射关系依然符合类余弦偶函数模型。

仿真条件与实验相同,设置回波信号的频率为 25 GHz,当两路信号功率差为 2 dB、4 dB 和 6 dB 时,对应的振幅比 r 分别为 0.7943、0.6310 和 0.5012。在 $\pm 180^\circ$ 范围内以 10° 为步长调节移相器并扫描相位差 φ ,仿真得到的归一化功率与理论功率-相位映射曲线如图 8(a) 所示,依据功率反推的仿真相位误差如图 8(b) 所示。由图 8(a) 可见,在 φ 为 0° 时,随着功率差的增大,干涉相消效果逐渐减弱,残余功率增加。图 8(b) 显示,在 φ 接近 180° 的区域,仿真相位误差显著增大,且该误差随两路信号功率差的增大而增大。因此,在实际 AOA 测量系统中,为确保高精度测角,需要在测量前对两路回波信号进行功率校准,尽可能使振幅一致,从而抑制由功率不平衡引入的附加测量误差。

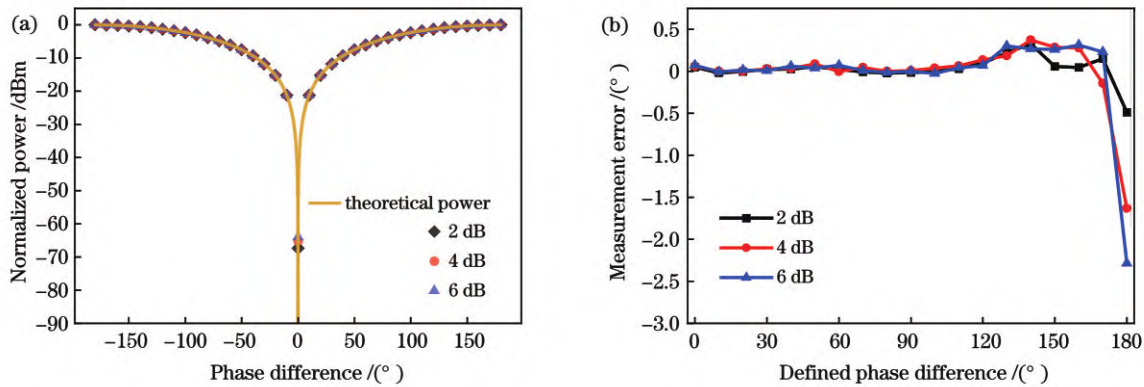


图 8 功率不平衡对相位差测量的影响。(a) 仿真功率与理论功率对比;(b) 仿真相位差与理论相位差的误差

Fig. 8 Effect of power imbalance on phase difference measurement. (a) Simulated power versus theoretical power; (b) error between simulated and theoretical phase differences

此外,实际 AOA 测量中面临的回波信号多为宽带形式,为验证该系统对宽带信号的适配能力,本文进一步开展了宽带信号 AOA 测量数值仿真。仿真设置如下:双波长频率间隔 $\omega_1 - \omega_2$ 为 30 GHz,回波信号采用中心频率为 25 GHz、带宽为 1 GHz、脉宽为 4 μ s、占空比为 1 的线性调频信号,系统对应得到的下变频信号 $\omega_1 - \omega_2 - \omega_{RF}$ 频率范围为 4~5 GHz。在 $-180^\circ \sim 180^\circ$ 范围内调节其中一路回波信号的移相量,并观测 $\omega_1 - \omega_2 - \omega_{RF}$ 的功率变化。图 9(a)、(b) 分别给出了 φ 为 0° 和 -180° 时的输出频谱,其结果与单音信号情况下的变化趋势一致。以 30° 为步长采集不同相位差下的信号功率,结果如图 9(c) 所示,实测归一化功率值与功率-相位映射理论模型吻合良好。由此推算得到的 AOA 测量值及测量误差如图 9(d) 所示。需要说明的是,宽带信号的功率-相位映射依赖于频带内的总功率,其功率提取精度受积分带宽选择及频谱平坦度等因素影响,功率提取误差将直接引入额外的测量误差,

进而影响相位解算与 AOA 估计的准确性。因此,在配备高精度功率检测与频谱积分处理的条件下,该系统可同时支持单频与宽带射频信号的 AOA 测量。

4 结 论

本文提出并验证了一种基于波长选择调制芯片的微波光子 AOA 测量方案。该方案采用类马赫-曾德尔干涉仪结构,通过级联 MRRs 与 PMs,实现了空间相位差至电信号功率的精准映射。实验结果表明,该系统成功将 20~30 GHz 的高频回波信号下变频至低频探测,在 $10^\circ \sim 170^\circ$ 范围内,相位测量误差不超过 $\pm 2.23^\circ$;天线间距设为半波长时,解算所得 AOA 在 $0^\circ \sim 70.8^\circ$ 范围内的测量误差不超过 $\pm 2.31^\circ$ 。此外,本文还分析了通道间回波信号功率不平衡对测量精度的影响以及系统的宽带适配性。本研究为开发小型化、低功耗微波光子 AOA 测量系统提供了一条有效的技术路径。

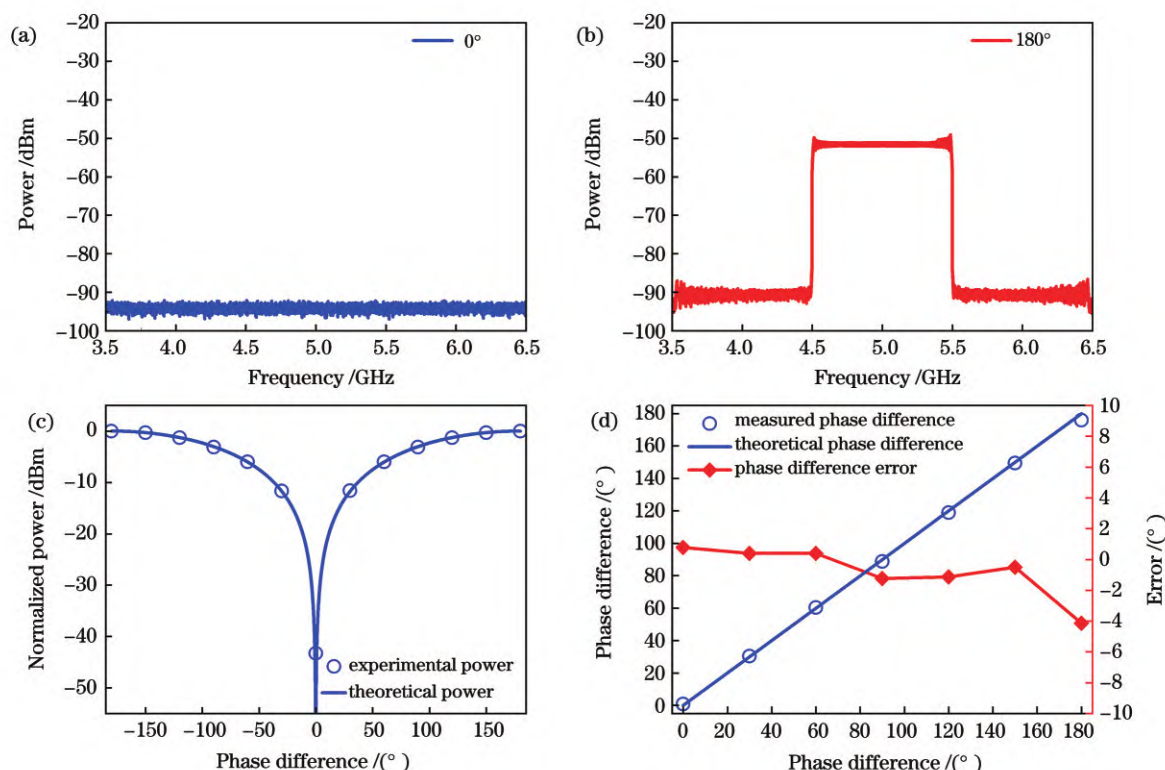


图9 宽带信号 AOA 测量结果。(a)宽带信号 $\omega_1 - \omega_2 - \omega_{RF}$ 的频谱(0°);(b)宽带信号 $\omega_1 - \omega_2 - \omega_{RF}$ 的频谱(180°);(c)宽带信号的相位差测量值与理论值间的误差;(d)宽带信号的 AOA 测量值与理论值间的误差

Fig. 9 Broadband signal AOA measurement results. (a) Spectrum of broadband signal $\omega_1 - \omega_2 - \omega_{RF}$ (0°); (b) spectrum of broadband signal $\omega_1 - \omega_2 - \omega_{RF}$ (180°); (c) error between measured and theoretical phase differences for broadband signal; (d) error between measured and theoretical AOAs for broadband signal

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Microwave Photonic Angle-of-Arrival Measurement Based on Wavelength-Selective Modulation Chip (Invited)

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Abstract

Objective Angle of arrival (AOA) is a critical physical parameter characterizing the propagation direction of wireless signals, and it has important application value in detection, communication, electronic countermeasures, and other fields. As the electromagnetic environment becomes increasingly complex, conventional electrical AOA measurement methods suffer from inherent electronic bottlenecks, which result in limited operating frequency, insufficient bandwidth, and weak anti-interference capability. Microwave photonic technology, leveraging its advantages of large bandwidth, low loss, and strong immunity to electromagnetic interference, offers a new approach for high-precision AOA measurement. Among existing microwave photonic AOA solutions, the power-phase mapping mechanism stands out in terms of system complexity, real-time performance, and measurement accuracy. However, most of these schemes are still based on discrete optoelectronic devices, which suffer from large footprint, high power consumption, and limited stability, making them unsuitable for application scenarios such as robotics and unmanned aerial vehicles that demand high integration and reliability. In recent years, the development of integrated photonic platforms such as lithium niobate on insulator (LNOI) has provided a viable pathway toward on-chip microwave photonic AOA measurement. Therefore, this paper designs and fabricates a wavelength-selective modulation chip based on the LNOI platform to achieve high-precision AOA detection, providing key technical support for the development of miniaturized, low-power, and high-precision microwave photonic AOA measurement systems.

Methods This paper proposed and experimentally validated a microwave photonic AOA measurement scheme based on a wavelength-selective modulation chip. The system comprised a light source module, an on-chip modulation module, and a photoelectric conversion module. The on-chip modulator was developed on the LNOI platform and adopted a Mach-Zehnder

interferometer-like structure, with cascaded micro-ring resonators (MRRs) and phase modulators (PMs) integrated into two parallel waveguide branches. The MRRs enabled wavelength selection, while the PMs achieved independent modulation of the separated optical carriers. The light source section employed an external modulation scheme consisting of a laser and a Mach-Zehnder modulator. By adopting carrier-suppressed double-sideband modulation, dual-wavelength coherent light was generated, with its frequency interval matching the resonance peak spacing of the MRRs. The radio-frequency echo signals received by two antennas were respectively loaded onto the PMs in the two arms. The two modulated optical signals were coherently combined on chip and then fed into a photodetector for beat-frequency detection, outputting a low-frequency electrical signal. By measuring the power of this low-frequency signal and utilizing the established power-phase mapping, the phase difference between the two received signals could be extracted; thereafter, the AOA value was calculated according to the antenna baseline spacing and the signal wavelength. Leveraging the 3 dB bandwidth of the MRRs, the system flexibly adjusted the dual-wavelength optical source interval to achieve down-converted detection of echo signals at 20 GHz, 25 GHz, and 30 GHz, respectively. Additionally, simulation analysis was conducted to investigate the impact of power imbalance between channels on angle measurement accuracy. Furthermore, numerical simulations were conducted to investigate the power imbalance between parallel channels, and its influence on angle measurement accuracy was quantitatively evaluated.

Results and Discussions This paper innovatively proposed a wavelength-selective modulation chip architecture, in which cascaded MRRs and PMs were integrated into the two parallel waveguide arms of a Mach-Zehnder interferometer-like structure. This design consolidated the functions of wavelength selection and independent signal modulation onto a single LNOI chip, enabling on-chip optical signal separation, independent modulation, and coherent combination. By mapping the phase information of echo signals to the power of demodulated signals and optimizing the frequency matching between the dual-wavelength light source and echo signals, this architecture successfully achieved photonic down-conversion detection of high-frequency echo signals. In the AOA measurement experiments, the system successfully down-converted 20 GHz, 25 GHz, and 30 GHz echo signals to 5 GHz low-frequency components for detection, which significantly reduced the burden of back-end data processing. By adjusting the phase shifter to simulate phase differences from -180° to 180° , the measured power-phase mapping curve was highly consistent with the theoretical cosine-like even function model. Within the phase-difference measurement range of 10° – 170° , the phase measurement errors at all three frequency points were below $\pm 2.23^\circ$, verifying the excellent mapping consistency of the architecture over a wide bandwidth. When the antenna spacing was set to half the wavelength, the phase difference range of 0° to 180° corresponded to an AOA range of 0° to 90° , with an effective measurement range of 0° to 70.8° and a corresponding AOA measurement error of less than $\pm 2.31^\circ$. Error analysis indicated that the accuracy of phase measurement was dependent on power sensitivity; when the phase difference approached 180° , the sensitivity of power to phase approached zero, resulting in increased phase retrieval error. Furthermore, simulation results regarding power imbalance between the two echo signals showed that an increased power difference reduced the interference contrast, indicating that channel power calibration was required in practical applications.

Conclusions This paper designed and validated a wavelength-selective modulation chip based on the LNOI platform, successfully demonstrating an on-chip integrated solution for microwave photonic AOA measurement. The system adopted a Mach-Zehnder interferometer-like structure, achieving the separation and independent modulation of dual-wavelength optical carriers through cascaded MRRs and PMs, and accurately mapping the phase difference information to the power distribution of the down-converted signals. Experimental results show that within the frequency band of 20–30 GHz, the phase difference measurement error of the system is better than $\pm 2.23^\circ$ in the range of 10° – 170° , and the AOA measurement error is less than $\pm 2.31^\circ$ in the range of 0° – 70.8° under half-wavelength antenna spacing. This paper also analyzed the effect of power imbalance of echo signals between channels on measurement accuracy as well as the broadband adaptability of the system. This work provides an effective technical pathway for the development of miniaturized, low-power microwave photonic AOA measurement systems.

Key words microwave photonics; angle-of-arrival measurement; integrated photonics; lithium niobate on insulator; micro ring resonator