光学学报

无源光互连中的改进型无波长冲突接收机

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摘要 在基于阵列波导光栅(AWG)的光互连数据中心中，提出了一种改进的多信道矩阵接收方案，该方案允许每个节点同时接收任意一组波长。该方案基于差错控制编码理论设计了只需要使用少量接收机、固定波长滤波器和一个波长可变滤波器的组合。通过OptiSystem软件仿真验证了在10 Gbit/s和40 Gbit/s的传输速率下，新旧接收方案的接收差异。实验表明，该方案可以有效降低发射功率和减少接收端所需固定波长滤波器的数量，节约了数据中心的设备成本和功耗。

关键词 光通信；光互连数据中心；阵列波导光栅；矩阵接收
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1 引 言

在全球数字化技术快速发展的时代背景下，大量的数据需要数据中心来存储和交换。根据预测，我国数据每年平均增量超过50%，预计到2025年我国将成为数据量最大、数据类型最丰富的国家[1-4]。传统的数据中心大多采用电互连的方式，然而电互连功耗较大且逐渐不能满足数据中心网络(DCN)高带宽的需求[5-6]。无源光学互连网络(POI)因其低功耗、低成本、高带宽和高透明度受到了广泛关注[7-8]。

DCN上的流量主要有机架内流量、机架间流量以及数据中心间流量[9-10]。数据中心的内部功耗、设备成本和网络阻塞问题都不可忽视，如何解决它们成了主要研究方向[11-13]。文献[14]中设计了一种软件定义机架内无源光互连网络(SD-POIRN)结构，数据平面采用光耦合器互连同一机架的服务器，控制平面采用软件定义的集中控制器协调机架内的数据通信，并提出了软件定义的介质访问控制(SD-MAC)机制。SD-MAC利用服务器发送分组与接收分组的思想，通过最大-最小公平共享带宽分配算法为服务器分配波长与时隙，避免数据传输发生碰撞。文献[15]提出了一种基于两级$N\times N$型阵列波导光栅(AWG)级连结构的数据中心内部的光网络互连结构，该方案可以同时满足数据中心机柜内部与机柜之间的互联需求。基于该结构使用线路交换，介绍了一种采用多路径和增加收发机数量的方案，有效降低了网络的阻塞率。文献[16]中提出了一种无缓存的环形闭合(Ring-Clos)架构。Ring-Clos架构以阵列波导光栅路由器(AWGR)为中间级，采用环形闭合交换机的并行调度(CDRC)算法为光分组分配路径，通过级内连接与可调波长转换器为光分组提供相邻中间级路由，解决了部分输入级或中间级输出端口的波长冲突问题。

文献[7]提出了一个方案，采用交错混叠的滤波范围和后续的接收信号运算可以实现少数固定波长接收机同时接收多个任意波长的信号，有效地降低了成本。然而这种方案中，随着AWG中波长总数的增长，每个节点所需的固定波长滤波器及接收机的数量F也不断增长，会造成大量接收机的闲置。本文提出了一种由一个可调波长滤波器(TF)和少量固定波长滤波器(FF)组合的方案，该方案能有效减少所需滤波器和接收机的数量，节约设备成本、减少设备功率损耗并提高信号的解调效率。

2 基本原理

基于AWG互连的POI阻塞图如图1所示。每个节点通常配备有用于数据传输和接收的波长可调发射器(WTT)和接收器(RX)。由于$N\times N$型AWG的循环波长路由特性，每个节点可以通过WTT向任何其他节点发送信号，因此可能出现多个节点向同一个目的节点发送数据的情况。节点和发送波长之间的关系为：节点i通过$\lambda_{(j-i)\bmod N+1}$向节点j发送数据，例如，节点1通过$\lambda_2(\lambda_N)$向节点2(节点N)发送数据。针对这种阻塞现象，本文提出了一种改进型的多信道矩阵接收方案，如图2所示。

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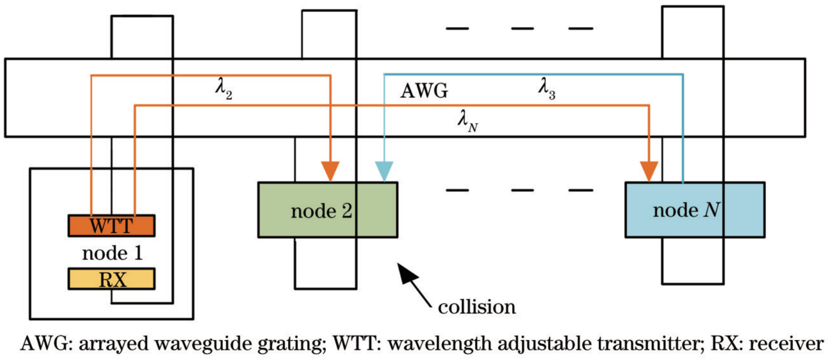

图1 基于AWG互连的POI阻塞图

Fig. 1 POI blocking diagram based on AWG interconnect

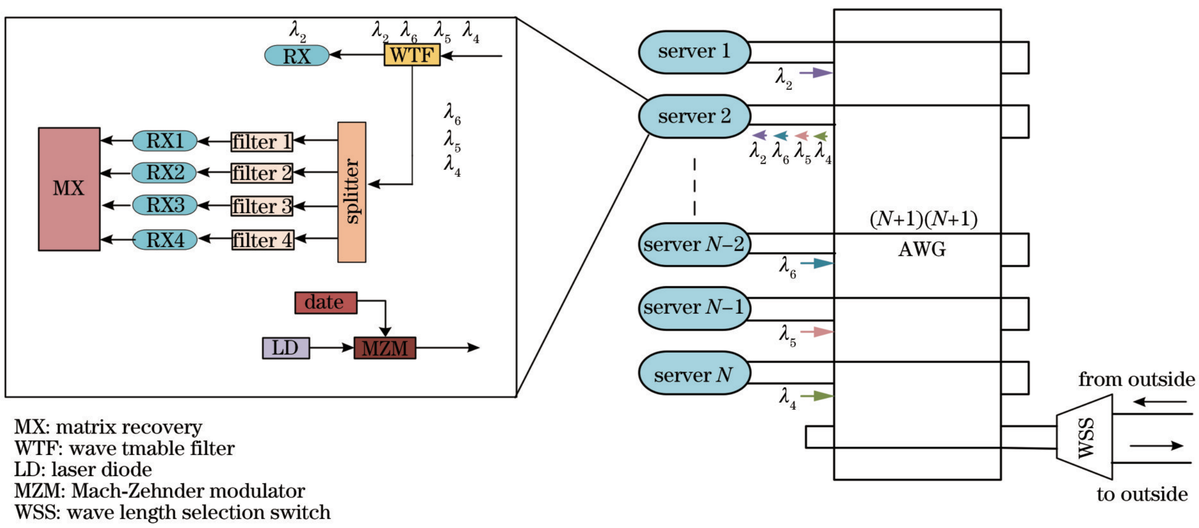

图2 基于改进的多信道矩阵接收的数据中心光互连结构

Fig. 2 Data center optical interconnect structure based on improved multi-channel matrix reception

该方案使用一个TF和几个FF组成的滤波器组来分离同时到达的几个信号。数据中心的机架中，一个AWG连接N个服务器，剩余的一个接口用于机架内和机架外间信号的通信。某时刻，服务器1、N-2、N-1和N要同时发送数据给服务器2，则它们将各自的激光器波长分别调整为λ_2、λ_6、λ_5和λ_4，并通过马赫-曾德尔调制器(MZM)调制信号后进入AWG，利用AWG波长路由特性，各个波长信号都会路由到服务器2的接收端。服务器2接收端通过TF滤出一个波长λ_2，然后将剩余3个波长的混合信号发送到滤波器矩阵进行信号恢复。

滤波器矩阵的设计思路与文献[7]中类似，各个滤波器的滤波范围交错混叠。如图3所示，各滤波器的滤波范围组成一个接收机矩阵，每个能被过滤的波长对应矩阵的一列，每个FF可以过滤的波长对应矩阵的一行。其中1代表该滤波器可以过滤该波长，0则不能过滤该波长。在文献[7]中已论证，当且仅当同时抵达的波长对应的接收器矩阵列线性独立时，可以恢复

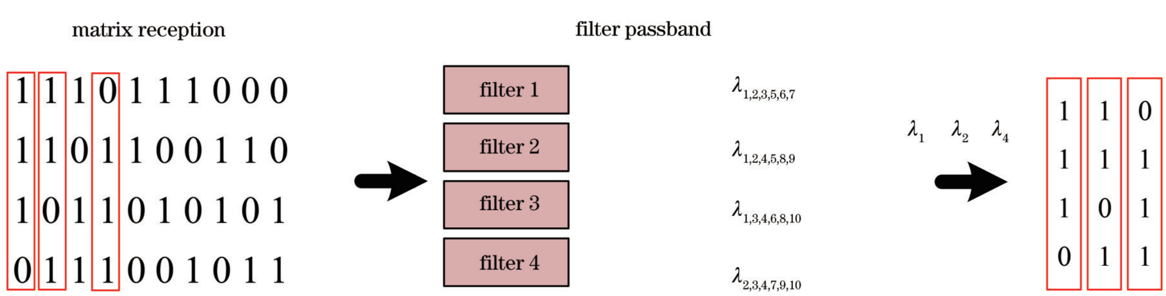

图3 矩阵接收原理图

Fig. 3 Schematic diagram of matrix reception

由不同波长承载的信号。与文献[7]中不同的是，本方案采用了一个TF，因此，即使4个波长信号同时抵达一个服务器，其FF组也只需要分离3个波长信号。文献[9]中已论证，要实现任意3个波长信号的分离恢复，所需的固定滤波器数量F应满足$\log_2^{F+1} \geqslant 3$。假设总波长数为10，为了确保由任意3个波长携带的数据能够被恢复，需要4个FF来分离恢复。例如某服务器接收到的信号波长分别为λ_1、λ_2和λ_4，如图3所示，这3个波长对应矩阵接收的1、2和4列，它们之间是线性无关的，因此是可以解调出来的。该滤波器矩阵可以分离恢复任意3个波长的信号，但是不能确保4个波长信号的分离恢复。例如接收信号为λ_2、λ_3、λ_9和λ_{10}时，对应的矩阵列第2、3、9和10列是线性相关的，是不能解调出来的。

3 测试结果及分析讨论

本文使用OptiSystem软件对数据中心中单节点出现接收冲突的情况进行了模拟仿真。仿真中，多个节点同时向一个节点发送数据，发射信号采用相同的伪随机二进制序列(PRBS)码，但排序不同，来控制几路光信号的发射光功率保持一致。接收端分别采用文献[9]中的多个FF组合和本文提出的一个TF加上几个FF组合来分析比较。信号的传输速率分别设置为10 Gbit/s和40 Gbit/s。部分仿真参数如表1所示。

表1 仿真参数

Table 1 Simulation parameters

Optical component	Extinction ratio of MZM /dB	LD laser frequency /THz	FF frequency /THz	TF frequency /THz	All filter bandwidth /GHz
Server 1	14	193	—	—	—
Server 2	14	—	193.2 193.3 193.4	193	50
Server $N-2$	14	193.4	—	—	—
Server $N-1$	14	193.3	—	—	—
Server N	14	193.2	—	—	—

首先模拟了4个节点同时向1个节点发送流量的情况，4个节点的发送波长分别为1552.5、1551.7、1550.9、1550.1 nm，在纯FF组成的接收端中，接收信号最多将是4个信号的混叠。而在本文提出的方案中，由于TF已滤出一个波长，从而滤波器组最多接收3个信号的混叠，因此信号质量更好。文中的误码率都是根据眼图的Q值估算得来的，单眼图的误码率(BER)为

$$R_{\mathrm{BER}} = R_{\mathrm{PE01}} + R_{\mathrm{RE10}} = \frac{1}{4}\mathrm{ERFC}\left(\frac{T_{\mathrm{H1}} - \mu_0}{\sqrt{2\sigma_0}}\right) + \frac{1}{4}\mathrm{ERFC}\left(\frac{T_{\mathrm{H1}} - \mu_1}{\sqrt{2\sigma_1}}\right), \quad (1)$$

式中：R_{PE01}为发送0码接收到1码的概率；R_{PE10}为发送1码接收到0码的概率；ERFC( )为互补误差函数；T_{H1}为判决门限；μ_x为每个电平的均值；σ_x为每个电平的方差。对于接收到的信号不需要解码，叠加的眼图可以通过式(1)计算单个眼图的BER，取其中最差的一个当作接收端的BER。

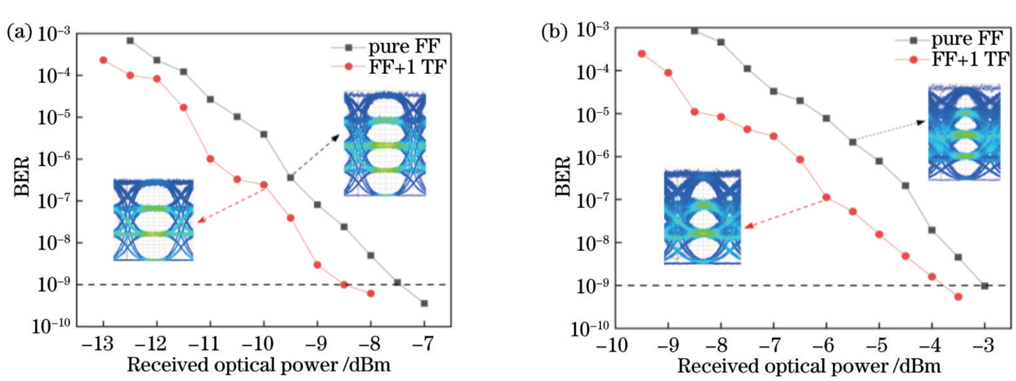

图4 4路波长信号同时抵达时的接收BER及眼图。(a) 10 Gbit/s传输；(b) 40 Gbit/s传输

Fig. 4 Bit error rates (BERs) and their eye diagrams when 4 wavelength signals arrive at same time. (a) 10 Gbit/s transmission; (b) 40 Gbit/s transmission

传输速率为10 Gbit/s时，如图4(a)所示，纯FF方案的接收灵敏度(无误码传输的光功率)为−7.1 dBm，本文所提出的TF+FF方案的接收灵敏度为−8.3 dBm，光接收功率之差为1.2 dBm。传输速率为40 Gbit/s时，如图4(b)所示，纯FF方案的接收灵敏度为−3.0 dBm，TF+FF方案的接收灵敏度为

−3.8 dBm,光接收功率之差为0.8 dBm。

数据中心光互连在实际当中,同时到达的波长数量3和2的情况占多数。因此用前文的两种接收方案测量了同时接收3个信号时的情况,如图5(a)所示,当采用纯FF接收时,10 Gbit/s传输速率时接收灵敏度为−8.2 dBm,采用TF+FF方案的接收灵敏度为−10.3 dBm。它们之间的光接收功率之差为2.1 dBm。如图5(b)所示,采用40 Gbit/s传输速率时,纯FF方案的接收灵敏度为−4.7 dBm,TF+FF方案的接收灵敏度为−6.3 dBm,光接收功率之差为1.6 dBm。

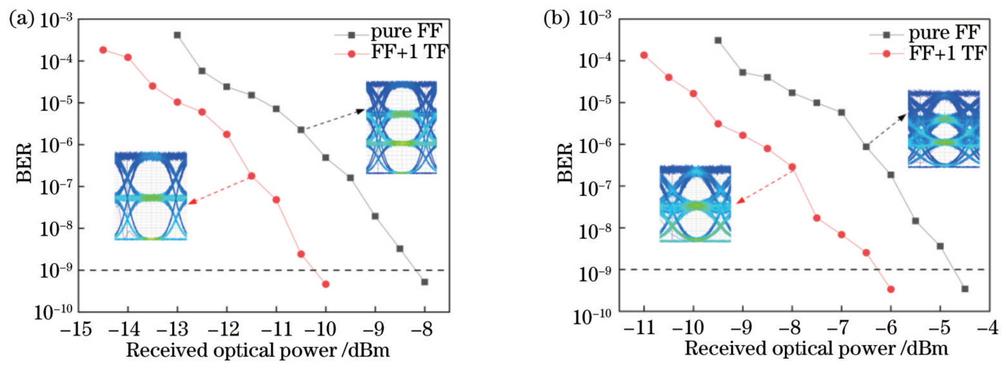

图5 3路波长信号同时抵达时的接收BER及眼图。(a) 10 Gbit/s传输;(b) 40 Gbit/s传输

Fig. 5 BERs and their eye diagrams when 3 wavelength signals arrive at same time. (a) 10 Gbit/s transmission; (b) 40 Gbit/s transmission

当同时到达的信号数量为2时,如图6(a)所示,传输速率为10 Gbit/s时,纯FF方案和TF+FF方案的接收灵敏度分别为−10.3 dBm和−15.4 dBm,它们的光接收功率之差是5.1 dBm。如图6(b)所示,传输速率为40 Gbit/s时,纯FF方案的接收灵敏度为−6.6 dBm,TF+FF方案的接收灵敏度为−12.6 dBm,光接收功率之差为6 dBm。相较于文献[9]中的纯FF方案,本文提出的TF+FF方案能更有效地提升信号质量,降低BER。同时到达的波长数量更少时本方案对于信号质量的提升更明显。随着传输速率的增大,接收端需要更大的发射光功率。所有接收端的眼图如图7所示。

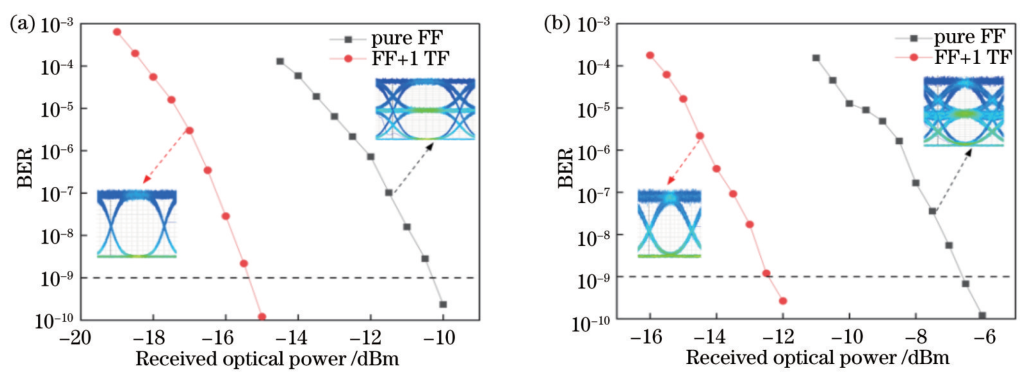

图6 2路波长信号同时抵达时的接收BER及眼图。(a) 10 Gbit/s传输;(b) 40 Gbit/s传输

Fig. 6 BERs and their eye diagrams when 2 wavelength signals arrive at same time. (a) 10 Gbit/s transmission; (b) 40 Gbit/s transmission

为了进一步验证提出方案的可行性,本文实验设置了4个10 Gb/s开关键控(OOK)信号,为了覆盖宽和窄信道间隔情况,波长分别选择为1530、1550、1555、1556 nm,在位同步和功率调整之后组合,然后由光电检测器检测。图8显示了接收信号的实测BER,图8(a)为未均衡的BER,图8(b)为均衡后的BER。

当到达第二代硬判决前向纠错编码(FEC)极限(即BER为3.8×10^{-3})时,如图8(a)所示,对于2个、3个和4个波长的组合,接收机灵敏度分别为−22.3、−19.8和−16.5 dBm。光接收功率之差为2.5 dBm和3.3 dBm。均衡后如图8(b)所示,对于不同波长的组合,接收机灵敏度分别为−22.9、−21.6、−19.0 dBm。光接收功率之差为1.3 dBm和2.6 dBm。图9为均衡后眼图。

信号的接收功率由信号发射功率减去链路损耗得到。在本文所提出的光互连结构中,接收信号的总链路损耗L可表示为

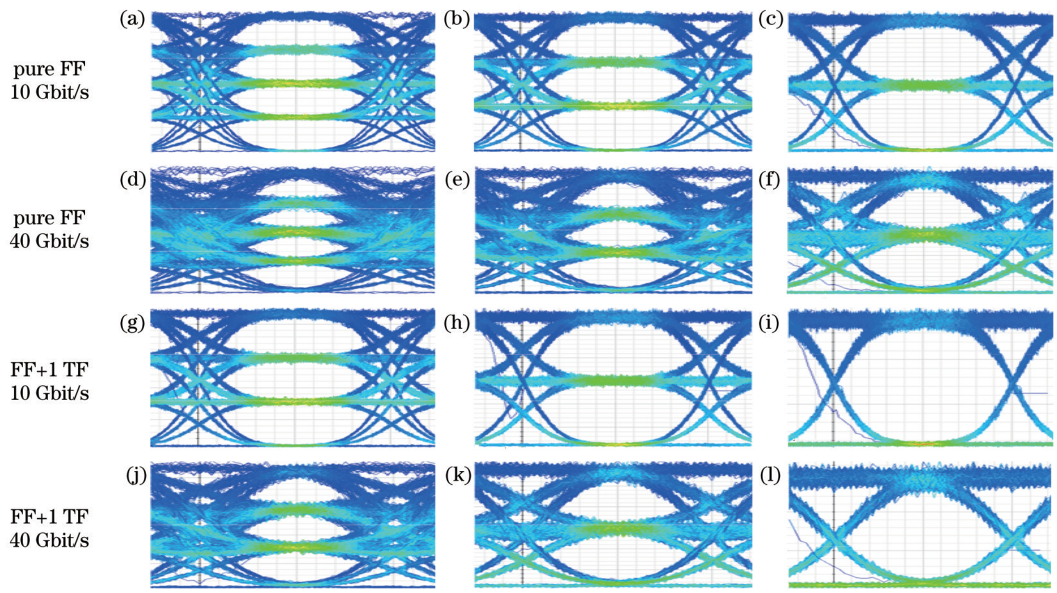

图 7 不同接收端和不同传输速率下的眼图集合。(a)、(d)、(g)、(j) 4 路信号；(b)、(e)、(h)、(k) 3 路信号；(c)、(f)、(i)、(l) 2 路信号

Fig. 7 Collection of eye diagrams at different receivers and different transmission rates. (a), (d), (g), (j) 4-way signal; (b), (e), (h), (k) 3-way signal; (c), (f), (i), (l) 2-way signal

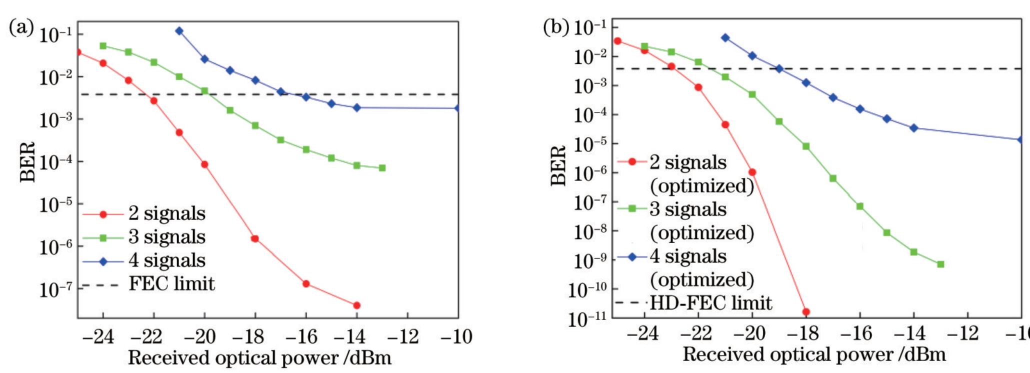

图 8 10 Gbit/s 下不同路信号到达时的 BER。(a)未均衡；(b)均衡后

Fig. 8 BER of different channel signals at 10 Gbit/s. (a) Unbalanced; (b) after equalization

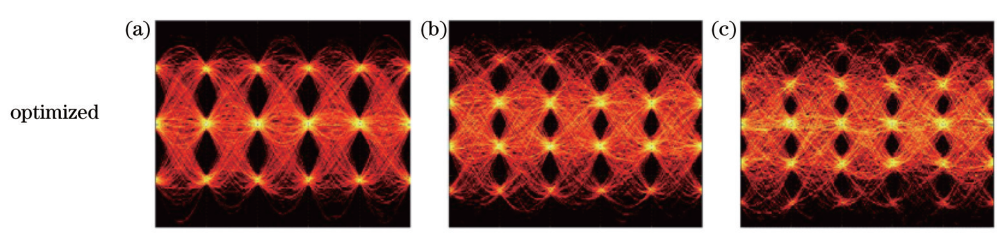

图 9 均衡后的眼图。(a) 2 路信号；(b) 3 路信号；(c) 4 路信号

Fig. 9 Eye diagrams after equalization. (a) 2-way signal; (b) 3-way signal; (c) 4-way signal

$$L = L_S + L_A + L_T + L_F, \tag{2}$$

式中：L_S 为分光器的损耗；L_A 为 AWG 的损耗；L_T 和 L_F 分别为 TF 和 FF 的损耗。L_S 的典型值为 $(10\lg F)$ dB，L_A 的典型值为 5 dB，L_T 和 L_F 的典型值为 1.5 dB。商用发射机的输出功率可以达到 9 dBm，10 Gbit/s 传输速率时混合接收灵敏度为 −8.3 dBm，允许的插值损耗为 17.3 dB，L_S 损耗最多可以支持 8 个 FF 组成的滤波器矩阵。由图 10[9]可知，提出方案可以支持多达 100 个波长在 AWG 中传输，利用 FEC 或光放大器可以进一步增加该值。

由文献[11]中计算所需滤波器数量与总波长数的公式，得到了同时到达的波长数(M)为 3 和 4 时所需滤波器的数量。如图 10 所示，随着总波长数的增加，M 为 3 和 4 时所需的滤波器数量之差是不断增加的。本文提出的方案添加一个 TF 把 M 为 4 的情况优化成 M 为 3 的情况，从而减少所需 FF 的数量，通过文献[8]调

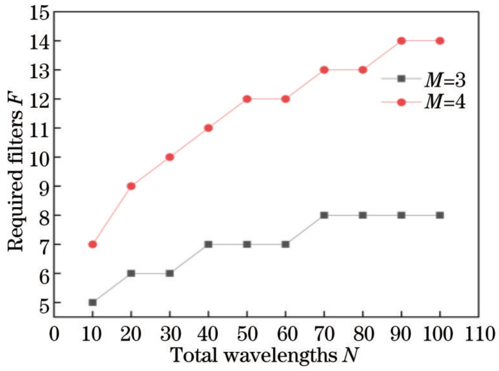

图 10 同时到达的波长数为 $M=3$ 与 $M=4$ 时所需滤波器和接收机数量的比较[9]

Fig. 10 Comparison of number of filters and receivers required when number of wavelengths reached simultaneously are $M=3$ and $M=4$[9]

查发现，一个 TF 的价格相当于 2.5 个 FF 的价格。从图中可以看到，优化后节约的 FF 的价格是远大于 1 个 TF 的价格的。随着工业化生产的进步，TF 的价格会更低，同时一个滤波器需要连接一个接收机接收其滤出来的信号。而且本方案中滤波器数量大大减少，也会大大降低服务器中的接收机总数，从而降低每个服务器的成本。整个数据中心的设备成本也大幅降低。从损耗方面来说，在不使用放大器和 FEC 时，功率预算只支持 8 个 FF 组成的滤波器矩阵，使用纯 FF 时仅允许十几个波长传输，改进后的方案则可以支持 100 个以上的波长传输。

4 结 论

为了避免基于 AWG 的无源光互连结构的接收冲突，在文献[7]和文献[9]提出方案的基础上，本文提出了一种改进的多波长接收方案。数据中心在基于 AWG 光互连的基础上，一个接收端采用一个 TF 和数个 FF 组合的方案，可以将同时接收的波长信号由 4 路($M=4$)优化到 3 路($M=3$)。这两种情况解调所需的滤波器数量之差随着数据中心内部波长总数的增加而增大。仿真测试结果表明，提出的改进方案对于信号质量有明显的提升，特别是在同时到达的波长信号较少时。通过计算功率损耗，得出改进方案在 10 Gbit/s 传输速率下最多可以支持 100 个波长在数据中心内部传输。本方案只需要添加一个 TF 就能明显减少所需 FF 及其连接的接收机的数量，可以有效减少设备成本和闲置滤波器及接收机的数量。

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An Improved Wavelength-Free Collision-Free Receiver for Passive Optical Interconnection

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Abstract

Objective The traffic on the data center network is mainly composed of intra-rack traffic, inter-rack traffic, and inter-data center traffic. The internal power consumption, equipment cost, and network congestion of the data center cannot be ignored. How to solve these problems has become a solution proposed by the main research. Using the interleaved filter range and subsequent received signal operation, a few fixed receivers (FFs) can receive multiple signals of arbitrary wavelengths at the same time, effectively reducing the cost. However, with the increase in the total number of wavelengths in the arrayed waveguide grating (AWG), the number (F) of FFs and receivers required by each node also increases, which will make a large number of receivers idle. Here we propose a scheme consisting of a tunable filter (TF) and a small number of FFs. This scheme can effectively reduce the number of filters and receivers required, save equipment costs, reduce equipment power loss, and improve signal demodulation efficiency.

Methods Due to the cyclic wavelength routing feature of $N \times N$ AWG, each node can send signals to any other node through the wavelength tunable transmitter (WTT), so multiple nodes may send data to the same destination node. The relationship between node and transmission wavelength $\lambda_{(j-i)\mathrm{mod}N+1}$ is that node i sends data to node j. For example, node 1 sends data to node 2 (node N) through λ_2 (λ_N) (Fig. 1). In the rack of the data center, one AWG is connected to N servers, and the remaining one interface is used for signal communication inside and outside the rack. At a certain time, if servers 1, $N-2$, $N-1$, and N want to send data to server 2 at the same time, they will adjust their laser wavelengths to λ_2, λ_6, λ_5, and λ_4. After the signal is modulated by the Mach-Zehnder modulator, it enters the AWG. By using the AWG wavelength routing characteristics, each wavelength signal will be routed to the receiving end of server 2. The receiver of server 2 filters a wavelength of λ_2 through a TF and then sends the mixed signal of the remaining three wavelengths to the filter matrix for signal recovery (Fig. 2). The filtering range of each filter forms a receiver matrix. Whether each wavelength can be filtered corresponds to a column of the matrix, and the wavelength that each FF can filter corresponds to a row of the matrix. Specifically, 1 represents that the filter can filter the wavelength, and 0 indicates that the filter cannot filter the wavelength (Fig. 3).

Results and Discussions When the transmission rate is 10 Gbit/s, the receiving sensitivity of the pure FF scheme (optical power of error-free transmission) is −7.1 dBm. The receiving sensitivity of the TF+FF scheme proposed in this study is −8.3 dBm, and the difference in optical receiving power is 1.2 dBm. When the transmission rate is 40 Gbit/s, the receiving sensitivity of the pure FF scheme is −3 dBm, and that of the TF+FF scheme is −3.8 dBm. The difference in optical receiving power is 0.8 dBm (Fig. 4). When pure FF reception is adopted, the receiving sensitivity of the scheme at a transmission rate of 10 Gbit/s is −8.2 dBm, and the receiving sensitivity of TF+FF scheme is −10.3 dBm. The optical receiving power difference between them is 2.1 dBm. When the transmission rate of 40 Gbit/s is adopted, the receiving sensitivity of the pure FF scheme is −4.7 dBm, and that of the TF+FF scheme is −6.3 dBm. The difference in optical receiving power is 1.6 dBm (Fig. 5). When the number of signals arriving at the same time is 2, and the transmission rate is 10 Gbit, the receiving sensitivity of the two schemes is −10.3 dBm and −15.4 dBm, and the difference in their optical receiving power is 5.1 dBm. When the transmission rate is 40 Gbit/s, the receiving sensitivity of pure FF scheme is −6.6 dBm, and that of the TF+FF scheme is −12.6 dBm. The difference in optical receiving power is 6 dBm. Our new TF+FF scheme can more effectively improve signal quality and reduce the bit error rate (BER). When the number of wavelengths arriving at the same time is less, the improvement of signal quality of the new scheme is more obvious (Fig. 6). When the second generation hard decision forward error correction coding (FEC) limit (BER is 3.8×10^{-3}) is reached, for the combination of two, three, and four wavelengths, the receiving sensitivities are −22.3, −19.8, and −16.5 dBm, respectively. The differences in optical receiving power are 2.5 and 3.3 dBm. After equalization, the receiving sensitivities are −22.9, −21.6, and −19.0 dBm for the combination of different wavelengths, and the differences in optical receiving power are 1.3 and 2.6 dBm, respectively (Fig. 8).

Conclusions An improved multi-wavelength reception scheme is proposed. On the basis of AWG optical interconnection, the data center adopts a scheme involving a TF and several FFs at one receiving end, which can optimize the simultaneous received wavelength signal from four channels (M=4) to three channels (M=3). The difference between the number of filters required for demodulation in these two cases increases with the increase in the total number of wavelengths in the data center. The simulation results show that the improved scheme proposed in this study can significantly improve the signal quality, especially when the number of wavelength signals arriving at the same time is small. By calculating the power loss, it is concluded that the improved scheme under 10 Gbit/s can support the transmission of up to 100 wavelengths in the data center. This scheme can significantly reduce the number of FFs and their connected receivers by adding only one TF and can effectively reduce the equipment cost and the number of idle filters and receivers.

Key words optical communication; data center of optical interconnection; arrayed waveguide grating; matrix reception