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厦门大学博士学位论文

基于全息菲涅耳透镜的波分复用光通信器件

Study on WDM Optical Communications Devices Based on Holographic Fresnel lenses

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Study on
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摘 要

社会信息化的发展对高速大容量通信网络的发展提出了迫切的要求。波分复用技术已经被公认是大容量光通信网络的主流技术。而光无源器件是构成光网络的基础。由于全息菲涅耳透镜具有良好和丰富的光谱特性，以及重量轻、成本低等优点，因此，本文认为基于全息透镜的新型光无源器件在波分复用网络中将有着广泛的应用前景。

本文对全息菲涅耳透镜的基本特性进行了深入的理论分析，以此为基础，着重探讨和研究了其作为解复用器和光耦合器的特性以及它们在波复用系统中的应用。

本论文的主要研究内容和创新之处包括：

指出全息菲涅耳透镜是一种特殊类型的光栅。分析并说明光栅的标量衍射理论是计算衍射效率的一种近似方法，因此它的应用是有限制条件的。继而提出本文所研究的对象应采用严格的耦合波理论来分析。

首次提出可以利用全息透镜的色散特性来完成波分复用系统中的分波功能。简要介绍了这类光学成像元件的前身—菲涅耳波带片，并概述了离轴全息透镜的制作、成像以及色散等光学现象，目的是为了证实以其为模型制作分波器的有效性和可行性。

由于本分波器能同时实现色散和聚焦两种功能，因此其明显优于其它类型的器件。文中总结了本课题组研究开发的全息型器件所拥有的优点和创新之处，并以示意图的方式阐明了其基本工作原理。

对本分波器可能存在的问题进行了研究和探讨：首先指出在制作器件过程中，应采取镀增透膜和加光阑等措施来降低可能引入的噪声。接着在详细分析光栅色分辨本领的基础上，推导出本复用器的分辨率与光栅结构等各项参数之间的关系，同时说明为使分辨率满足系统需求，对分波器表面被照射面积有一定的要求。最后通过对电子全息图实现可见光重现的描述，排除了放大全息图

以消除像差的有效性。继而提出利用像差补偿的方法，求解出优化的光路结构，以使重现波长不同于记录波长所产生的像差达到最小值。

为论证全息型分波器的空间频率、衍射效率和角色散能力之间的关系，设计出能实现指定波长间隔的分波器，本论文重点分析了 4 种制作光路，并对其制作的器件进行了比较和分析。同时从全息透镜的成像原理和分波器件的实际应用条件出发，本文选取了最优记录结构系统。

本文总结了波分复用系统中，为满足其系统方面的要求，判断性能的三个主要标准。重点分析了全息型分波元件的工作波长范围和其所能实现的理论线色散。在以上所选取的最优记录系统的基础上，根据具体情况对某些参数进行调整，制作了记录参数不同的 4 种全息分波器。通过分波器在可见光波段的测试，发现其已能将两不同波长的激光束在焦平面实现分离，分离距离与理论计算值相吻合。然后，在红外波段，使用带有接收尾纤的光谱仪进行性能参数的测量，并对所得数据进行了必要的讨论以优化分波器的制作系统。最后，总结出考虑像差因素所设计的分波器为最佳类型，同时列举了三个平均波长间隔为 25nm 的信道的信道带宽、插入损耗和串扰性能，以说明本器件已接近实用水平。

根据本文前面内容的分析，得出微型全息透镜还可应用于光源与光纤、波导之间的耦合。本论文对此进行了探讨和尝试，利用全息透镜的角放大率公式，设计并制作了一个全息型外耦合器，通过光纤耦合实验测得其耦合效率比直接耦合提高了一倍。本论文给出了初步的实验结果，并对结果进行了深入的分析和讨论。

本文最后总结了本项目由于时间和客观条件的限制，还存在的一些问题和今后改进的方案，以及产业化的设想。全息解复用器的不足之处有插入损耗较大，平均插入损耗约为 10dB，因此本论文考虑是否选取其它类型的全息记录材料，以提高全息衍射元件的衍射效率。另外，目前所能实现的波长间隔仅为 25nm，更密集的信道间隔有待进一步开发研究。

关键词：波分复用器；全息透镜；外耦合器

Abstract

The developing of information society raises an urgent request for high-speed, huge-capacity communication network. Wavelength Division Multiplexing (WDM) has been widely recognized as the main and most important technology to achieve huge-capacity optical communication network. Optical passive devices are the basis of optical networking. Because of their good and rich spectral characteristics, light weight and low cost, holographic Fresnel lenses (HFLs) and related new optical passive devices are believed to have wide applications in WDM network.

In this dissertation, based on the theoretical analysis of HFLs, we investigate the basic characteristics and applications in WDM network of some new devices, especially for optical multiplexer/demultiplexer and external coupler.

The main contents and innovations of this dissertation are as follows:

It is pointed out that HFLs are special gratings. We show and illuminate that the scalar diffraction theory is an approximation method to calculate the diffraction efficiency of grating, and there are restrictions on its application. The coupled-wave theory is introduced for our research objects.

It is proposed, for the first time, that the demultiplexing in WDM can be realized by the dispersion characteristic of holographic lens. To prove the feasibility and validity of holographic WDM, we introduce briefly the Fresnel zone plates, the predecessor of this kind of optical passive devices, and summarize the fabrication, imaging and dispersion of off-axis holographic lens.

Holographic WDM is superior to other generic devices since it has both functions of focusing and defocusing. Excellence and innovation of holographic WDM are presented in the issue, and the operating principle of the demultiplexer is illustrated by diagrammatic sketch.

Inherent issues in holographic WDM are investigated and discussed. Firstly, it is indicated how to depress the noise during operation process. Then on the basis of detailed analysis of grating resolution ability, we deduced the relation between resolution and grating parameters. We also showed theoretically that there is a lower limit of the irritation area to meet the system requirement in resolution. We show that zooming out hologram is not effective to cancel aberration by going through the process of reconstructing electron hologram with visible light. In the end, we point out one can minimize the wavefront aberration due to wavelength shift by optimizing configuration parameters of the optical holographic wavelength demultiplexer by the aberration redeeming method.

In order to demonstrate the relations among frequency, diffraction efficiency and dispersion ability of holographic WDM, and to design a demultiplexer with a pre-selected frequency channel, four recording optical configurations are analyzed in detail, and their related devices are compared and assayed in this dissertation. Optimal recording configuration is selected, with the aid of the imaging principle of holographic lens and practical application condition of WDM.

Three key criteria are provided for measuring the capability of demultiplexer. FSR and theoretical linear dispersion of holographic WDM are studied detailedly. Based on the optimized recording configuration, four demultiplexers with different recording parameters are manufactured according

to practical conditions. The testing in visible region shows their ability to separate two laser beams with different wavelengths on the focus plane, and the separating distances are consistent with the values from theoretical analysis. Then we optimize WDM by analyzing the experimental results of further testing in infrared region. In the end, we list the channel spacing, insertion loss and crosstalk of three channels with 25nm spacing, and conclude that the WDM is the best way to take care of aberration and our device is close to practical requirement.

According to the previous discussion, we found that micro holographic lenses can be used as the external couplers to couple the light emitted from a LD to a fiber, waveguide and so on. We designed and fabricated a holographic coupler, utilizing angle amplifier formula of holographic lenses and found it has twice coupling efficiency the direct coupling has. Embedded analysis and discussion are presented in the dissertation.

Finally, deficiencies in this device are summarized and their further improvements are discussed. For instance, the average insertion loss of this device is as high as 10dB, and we are considering other recording materials to enhance to the diffraction efficiency. Further investigations are needed for its industrialization.

Key words: multiplexer/demultiplexer；holographic lens；external coupler

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