Fabry-Perot Filter-Based Mode-Group Demultiplexers

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Abstract: A novel mode-group demultiplexer using Fabry-Perot (FP) filters has been proposed and designed to enable low-crosstalk demultiplexing of mode groups with degeneracies commensurate with those of graded-index (GRIN) MMFs. © 2020 The Author(s)

1. Introduction

To support increasing data capacity, space-division multiplexing (SDM) has been proposed to go beyond the capacity limit of single-mode fibers (SMF) [1]. Multimode fibers (MMF) can support mode-division multiplexing (MDM) but random modal crosstalk increases the complexity and cost of MDM transmission [2]. For short-distance applications, mode-group multiplexing (MGM) can be used without complex digital signal processing (DSP) [3]. In MGM, all modes in the same group carry the same data and because of the large effective index differences between mode groups, crosstalk between mode groups can be effectively suppressed. To support MGM, the most straightforward mode-group demultiplexer (MG DeMux) can be implemented by demultiplexing all spatial modes, followed by multiplexing degenerate modes in the same group using devices such as lanterns [1]. Such MG DeMuxes tend to have large component counts and associated insertion losses. Other approaches such as the degenerate-mode-selective coupler [3] can only demultiplex mode groups with two-fold degeneracies. All aforementioned methods can only support limited numbers of mode groups with relatively high crosstalk. In this paper, we present an MG DeMux that supports mode-group demultiplexing with degeneracies commensurate with mode degeneracies in GRIN MMFs. The structures of the MG DeMux is similar to that of wavelength-division multiplexing (WDM) DeMux using FP thin-film filters (TFFs) and facilitates MG demultiplexing with low crosstalk.

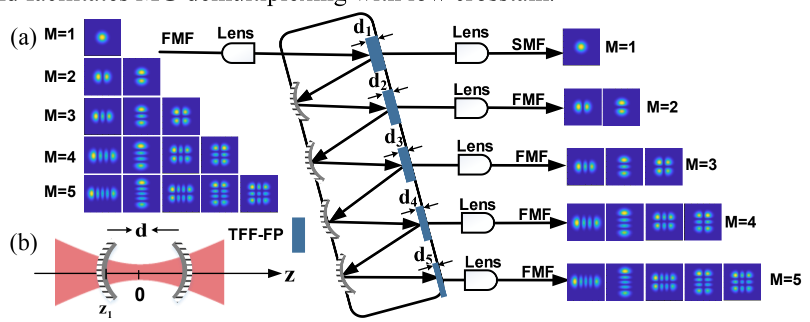

Fig.1:(a) Schematic of the MG DeMux based on FP resonators. The distances between mirrors $d_1, d_2, \dots, d_5$ should match the resonance conditions for the corresponding mode groups. (b) Schematic of an HG beam propagation and the positions of the mirrors.

2. Device Structure and Performance

Figure 1 shows the schematic of the proposed MG DeMux. When the incoming MGM signal carried on the same wavelength is reflected off successive FP filters, only one mode group is transmitted and the reflected signal is directed toward the next FP to be demultiplexed. This device exploits the mode-dependent filtering properties of FP resonators. To understand how this works, we analyze how Hermite–Gaussian (HG) beams of order (m, n) [4]

$$E_{mn}^{HG}(x,y,z) = A_{m,n}\frac{w_0}{w(z)}H_m\left(\frac{x\sqrt{2}}{w(z)}\right)H_n\left(\frac{y\sqrt{2}}{w(z)}\right)\exp\left(-\frac{x^2+y^2}{w^2(z)} - i\frac{k(x^2+y^2)}{2R(z)} - ikz + i(m+n+1)\tan^{-1}\left(\frac{z}{z_0}\right)\right) \quad (1)$$

propagate through FP filters. In Eq. (1), H_m and H_n are Hermite polynomials of order m and n, k is the wavenumber, x and y are the transverse coordinates and z is the longitudinal coordinate with its origin at the beam waist. The waist, Rayleigh range and the z-dependent beam radius of the Gaussian beam are w_0, z_0, and $w(z)$, respectively, $R(z)$ is the radius of curvature of the wavefront, which is independent of the mode orders. Therefore, all HG modes are eigen modes of spherical FP resonators [4]. This is because, if the radius of the curvature of the HG beam wavefront is equal to the radius of the FP mirror, all the points on each mirror share the same phase and the reflected beam will retrace the incident beam [5]. For an FP, the transmittance is $T = 1/(1+F\sin^2(\Delta\varphi/2))$ where $F = 4r^2/(1-r^2)^2$ is the finesse, r is the reflection coefficient of the mirrors, and $\Delta\varphi$ is the roundtrip phase shift, which depends on mirror separation d and the wavelength of the light. From Eq. (1), the phase of an HG_{mn} beam is:

$$\varphi(x,y,z)=\left(k(x^2+y^2)/2R(z)\right)+kz-(m+n+1)\tan^{-1}(z/z_0)\,. \tag{2}$$

Degenerate modes within the same transversal mode order $M=m+n+1$ but with different combinations of (m,n) share the same phase. Therefore, in an FP, if the first mirror is located at $z=z_1$ as shown in Fig.1(b), the round-trip phase shift is $\Delta\varphi=2kd-2M\Delta\xi(z_1)$, where $\Delta\xi(z_1)=\left\lfloor \tan^{-1}\left((z_1+d)/z_0\right)-\tan^{-1}\left(z_1/z_0\right)\right\rfloor$. At resonance frequencies

$$f_{q,M}=qFSR+M\Delta\xi(z_1)FSR/\pi\ , \tag{3}$$

where q is the longitudinal mode order, maximum transmission happens. The frequency separation between successive transmission peaks in the longitudinal order ($\Delta q=1$) for the same mode group, called the free-spectral range, is given by $FSR=c/2nd$, which is independent of the transverse mode order M. Based on Eq. (3), the mode-group spacing (Δf), defined as the resonance frequency difference between two adjacent transverse mode groups (ΔM=1) for a fixed q , is $\Delta f=\Delta\xi(z_1)FSR/\pi$. In particular, in a non-confocal resonator with $|z_1|\ll z_0$, $\Delta f=c/2\pi nz_0$ [6].

In the FP, if Δf is designed to be larger than the bandwidth (B) of the data carried on each mode group, only one mode group can transmit through a particular FP resonator and all other mode groups will be reflected back. Figure 2(a) shows the simulation results for transmission of a beam with five HG mode groups and z_0=200μm through an FP filter with n=1.5, FSR=4.959THz, and B=10GHz. This FP transmits the M=1 mode group and reflects all others at λ=1.55μm. To demultiplex the M=2 mode group at the same wavelength, the FSR of the next FP should be adjusted by using a slightly different mirror separation d. It should be noted that, for z_0= 200μm, flat mirrors will be adequate since $R(d)\approx 2mm$ and $w(d)\approx 10\mu m$, which allows the use of TFF-based FP resonators.

Based on Eq. (3), one can control the crosstalk by changing the Rayleigh range z_0. We define crosstalk as the summation of intensities of all unwanted mode groups at the resonance frequency of the desired one. For B=10GHz, n=1.5, z_0= 42μm, and FSR=5THz, the crosstalk is less than -40dB, which represents a significant improvement in comparison with other MG DeMuxes [1, 7]. Figure 2(b) shows how the crosstalk depends on FSR and z_0. For large z_0, different FSRs have similar crosstalk on the order of -15dB. By decreasing z_0, Δf increases and the crosstalk reduces initially. However, when z_0 is decreased further, the crosstalk increases, reaching a maximum when the resonance frequency of the desired mode group coincides with that of another mode group associated with the next longitudinal mode. For smaller z_0, Δf becomes larger than FSR and the chance of overlapping with other longitudinal modes increases. Therefore, for demultiplexing a fixed number of mode-groups using an FP with a specific FSR, there is an optimum z_0 for minimum crosstalk. Furthermore, as shown in Fig. 3(b), the crosstalk increases as expected when the data bandwidth carried on each mode group increases. To maintain low crosstalk, the FSR of the FP filter should be increased for demultiplexing large bandwidth MGM signals. Figure 3(b) shows that crosstalk less than -20dB can be achieved for B=100GHz and FSR=5THz.

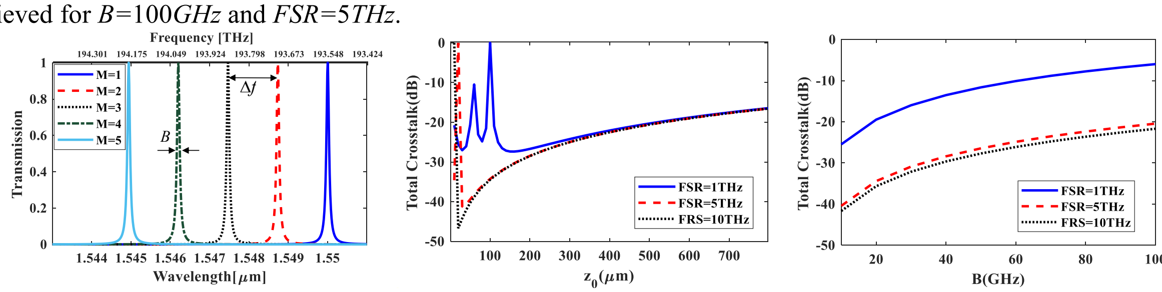

Fig.2: (a) Transmission of modes for FSR=4.959THz. (b) Crosstalk vs. z_0 and (c) Crosstalk vs. B for different FSRs for five mode groups.

3. Conclusion

In this paper, we present a novel mode-group demultiplexer. The structures of the MG DeMux is similar to that of TFF-based WDM filters. This is the only MG DeMux, to the best of our knowledge, that can support low-crosstalk mode-group demultiplexing with degeneracies commensurate with mode degeneracies in GRIN multimode fibers.

This work was supported in part by the Army Research Office under contracts W911NF1710553 and W911NF1810365, and NSF under grant numbers ECCS-1808976 and 1932858.

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