Optical Fiber Technology 20 (2014) 239–244

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Guidelines for design and fabrication of fused fiber coupler based wavelength division multiplexings

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ARTICLE INFO

Article history:
Received 29 July 2013
Revised 24 November 2013
Available online 5 March 2014

Keywords:
Wavelength division multiplexing
Fused fiber coupler
Coupling coefficient

ABSTRACT

The fused fiber coupler can be function as WDM (Wavelength Division Multiplexing). An analysis of the wavelength response of the fused fiber coupler is presented here. Both theoretical and numerical methods are used to calculate the wavelength channel spacing of WDM at different pulling stop cycles. Experiments were carried out to testify the calculation results. A combination of theoretical and numerical method is used to predict the channel spacing of WDM. The calculation agrees well with the experimental results. This paper provides some guidelines for design and fabrication of the fused fiber based WDMs.

1. Introduction

The fused biconical couplers have been widely used in the optical fiber system and network in the past twenty years. The commercialized fused-couplers dated from 1990s, and most research work is done in that period [1–3]. Since the fabrication process has been more sophisticated than the past, the properties of the fused coupler product (e.g. Excess Loss (EL), polarization dependent loss (PDL)) have been highly improved today. And less research work is dedicated on the theoretical work and fabrication parameters control. Some application of the fiber coupler in sensing area is reported recently [4,5].

Apart from function as optical power splitters, the fused couplers can also be properly designed as polarization beam splitters [6] and WDMs (Wavelength Division Multiplexing) [7]. Today the most commonly used fiber coupler based WDM is for wavelength 1310 nm/1550 nm. For 1480 nm/1550 nm or other wavelength range, the fiber coupler based WDM is more difficult to fabricate. Part of the reason is that as the wavelength spacing becomes shorter, the pulling length is harder to be accurately controlled. The initial motivation of this paper is to develop shorter wavelength spacing WDMs. Based on this motivation, an extensive study of the wavelength response of the fused fiber based 1×2 WDM was explored. Although some paper has done some work on the wavelength response of WDM [1,7,8], we found some wavelength spacing inconsistence with the predicted ones under nowadays fabrication conditions. This paper starts from a theoretical calculation of the coupling coefficient. A comparison of theoretical and numerical calculated coupling coefficients was made in Section 3. It is found that the fusion degree of the two fibers has some influence on the wavelength spacing of the WDM. The wavelength channel spacing of WDM at different pulling stop cycle was calculated both theoretically and numerically. A modification to the theoretical expression was made. The experimental results show good agreement with the modified calculation of the wavelength channel spacing. This study provides guidelines in the design and fabrication of shorter wavelength spacing WDMs. Some fabrication process parameter control is also useful for the industry.

2. The cross-section of the fused coupler

The coupling region of the fused coupler is composed of two stretched fibers. The schematic structure of the fusing-stretching part of one single fiber is shown in Fig. 1. It consists of a taper waist (W) and two taper regions ($L/2$). The taper waist (W) is also known as the flame width assuming the temperature distribution along the fiber coupler is entirely flat. And L is the pulling length. There are some mathematic model to describe the shape of the fused fiber [3,9]. Exponential expression is most commonly used to represent the taper shape [1,3]. The radius of the fused fiber decreases exponentially as the pulling length increases. Therefore the core-cladding mode coupling is gradually overtaken by the cladding-air coupling. The fiber cladding is assumed as the waveguide core. We define the radius ratio t as the ratio of the fused fiber cladding radius versus the initial fiber cladding radius (as shown in Fig. 1),

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http://dx.doi.org/10.1016/j.yofte.2014.02.005
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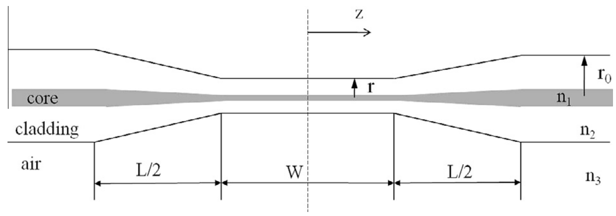

Fig. 1. Schematic structure of the fusing-stretching part of a single fiber.

$$t = \frac{r}{r_0} \tag{1}$$

where r_0 = 62.5 μm for single mode fiber. The WDM discussed in this paper is all for single mode fiber.

The schematic graph of the cross-section of the coupling region is shown in Fig. 2. In Fig. 2, d is the center to center distance between the two fibers; r is the radius of the fiber cladding; n_1, n_2, n_3, are the index of the fiber core, fiber cladding and air. We define the parameter D to describe the fusion degree of the two fibers,

$$D = \frac{d}{2r} \tag{2}$$

In the following section, the coupling coefficient of different fusion degree is calculated.

3. The coupling coefficient

There are two simple ways to describe the coupling mathematically. In the first method, the coupling coefficient is calculated by the perturbation theory. One fiber is assumed as a perturbation of the other fiber when two identical fibers are put close. The coupling coefficient is calculated by spatial overlap integral of the two interacting waveguide mode [10]. For weekly guiding condition, the mode profile of single fiber can be simply expressed by Bessel function. Therefore by overlapping the two individual mode profile of the fiber, the coupling coefficient of two fibers can be obtained [11],

$$C = \frac{(2\Delta)^{1/2}}{r} \cdot \frac{U^2}{V^3} \cdot \frac{K_0(Wd/r)}{K_1(W)} \tag{3}$$

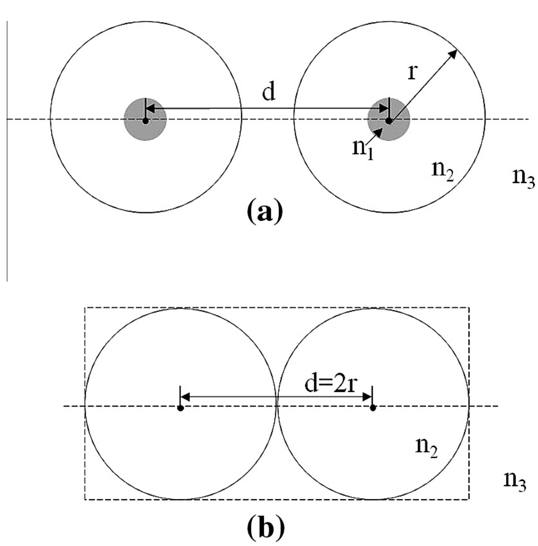

Fig. 2. Schematic graph of the cross-section of 1 × 2 fused coupler (a) $D > 1$ (b) $D = 1$.

where U, V, W, Δ are all parameters for the singe fiber; d is the center to center distance between the two fiber centers (Fig. 2); r is the radius of the fiber cladding (as shown in Fig. 2). K_0 is the modified Bessel function and K_1 is the second kind Bessel function; U, V, W, Δ is defined as,

$$\begin{aligned} &\Delta = (n_2^2 - n_3^2)/2n_2^2 \\ &V = k \cdot (n_2^2 - n_3^2)^{1/2} \cdot r, \quad k = 2\pi/\lambda \\ &U = r \cdot (k^2 n_2^2 - \beta^2)^{1/2}, \quad W = r \cdot (\beta^2 - k^2 n_3^2)^{1/2} \end{aligned} \tag{4}$$

where n_2 is the index of the fiber cladding, n_3 is the index of air ($n_3 = 1$), β is the propagation constant of the single fiber, λ is the transmission wavelength.

In the pulling process, as the decrease of the fiber radius, the fiber cladding serves the waveguide core ($n \approx 1.45$) and the air serves as the waveguide cladding ($n = 1.0$). Light in the fiber cladding is well confined, thus in Eq. (4), $\beta \approx kn_2$, $W \approx V$, Eq. (3) can be expressed symbolically as,

$$C = \frac{2}{r} \cdot \left(\frac{\Delta}{2\pi D}\right)^{1/2} \cdot \frac{U_\infty}{V^{5/2} e^{V(2D-2)}} \tag{5}$$

where $D = d/2r$, $U_\infty = 2.405$.

Eqs. (3) and (5) are more accurate for the weekly coupling conditions compared to the strong coupling conditions. As the two fibers come closer, Eq. (5) becomes less accurate [11]. The critical condition is $D = 1$ ($d = 2r$) in the case of two touching cores (Fig. 2(b)).

In the other method of describing the coupling mechanism, the two-fiber waveguide is taken as a composite waveguide. Since the radius of the tapered fiber varies slowly along the propagation axis, it can be assumed that only the first mode (even mode) and the second mode (odd mode) of the composite waveguide are excited. The mode profile of the fiber coupler can be described as a superposition of the two supermodes of the composite waveguide. Since the two modes have different propagation constant, the optical power beats back and forth between the two fibers. The coupling coefficient C is half difference of the propagation constant of the two modes,

$$C = \frac{\beta_+ - \beta_-}{2} \tag{6}$$

where β_+ is the even mode (a line-symmetric mode) of the composite waveguide, β_- is the odd mode (a point-symmetric mode) of the composite waveguide.

From Eq. (6), we can see that the coupling coefficient is obtained as long as the propagation constant of supermodes of the composite waveguide is known. In the past, some effort has been made to calculate the propagation constant of the supermodes of the composite waveguide by some numerical methods [2,12,13]. In this paper, we use finite element method to calculate the propagation constant of the supermodes of the composite waveguide.

To simplify the problem, a rectangular cross-section is used to represent the two fiber composite waveguide (as shown in Fig. 2). A symbolic expression of the coupling coefficient is obtained by theoretically calculating the propagation constants of the slab waveguide [14,15],

$$C = \frac{\beta_0 - \beta_1}{2} = \frac{3\pi\lambda}{32 n_2 a^2} \cdot \frac{1}{(1 + 1/V)^2} \tag{7}$$

where β_0 and β_1 are the propagation constant of the first mode and second mode of the slab waveguide; n_2 is the index of the fiber cladding; a is the diameter of the fiber; $V = ka \cdot (n_2^2 - n_3^2)^{1/2}$, $k = 2\pi/\lambda$.

We calculated the coupling coefficient both theoretically and numerically. We first calculated the coupling coefficient by using Eq. (5) for the touching core condition ($D = 1$, $d = 2r$) at wavelength