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Realization of Tapered Waveguide by Stretching the Rod Waveguide

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Abstract: By stretching the rod waveguide with different velocities in opposite directions, the tapered waveguide can be fabricated. In condition of taking no account of volume expansion caused by heating and under the assumptions of volume conservation, the rod waveguide can be stretched freely in the heated region without being stretched outside of the heated region. A model, which shows the relation of the transition shape and the two factors, that is the ratio of two velocity and the heated region length, is presented for the shape of the taper transition through mathematic deduction. Based on this model, a desired tapered waveguide can be fabricated. The tapered waveguide are widely used for fabricating tapered fiber couplers and sensors. In addition, the conclusion can be used for fabricating fused fiber coupler.

Key words: Optical fiber coupler; Tapered waveguide; Model

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1 Introduction

Recently, tapered waveguide is widely used for fabricating the integrated optical devices, especially for fabricating the optical fiber coupler[1] and sensor[2], and nowadays is used in microstructured optical fiber[3]. Moreover, the split power ratio of the optical fiber coupler which is fabricated in the tapered waveguide is weakly dependent on the wavelength. So, this kind of coupler is superior to others in respect of the bandwidth.

2 Model

2.1 Structure after Stretch

The shape of the tapered waveguide showing in Fig. 1 by stretching the rod waveguide was observed in many experiences. In Fig. 1, r_0 stands for the radius before stretching the rod waveguide; r_w the radius of mixing — rod after stretching the rod waveguide; z_1 the position from the point P in z direction; z_2 the position from the point Q in z direction ; z_{10} the tapered length in left end ; z_{20} the tapered length in right end; l_w the length of the waist; $r_1(z_1)$ the radius in the position z_1 of the left tapered rod; $r_2(z_2)$ the radius in the position z_2 of the right tapered rod. We can easily obtain from Fig. 1

$$r_1(0) = r_2(0) = r_0 \qquad r_1(z_{10}) = r_2(z_{20}) = r_w \tag{1}$$

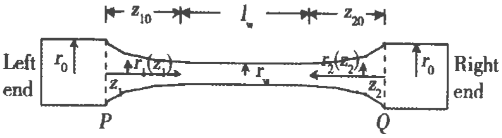

Fig. 1 The shape after stretching

2.2 Model

During being stretched, assume that the waveguide in the condition where the temperature of waveguide in the hot—zone is uniform is fully fused and can be stretched freely without being stretched by self—gravity. Outside the hot—zone, the waveguide can not be stretched completely.

The waveguide shape pulled at time t is shown in Fig . 2 . To keep the shape as shown in Fig . 2 , the

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following relation should be met.

$$L(t) > 0 \qquad l_w = L(t) \tag{2}$$

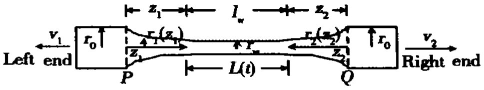

Fig. 2 The shape of the waveguide at time t

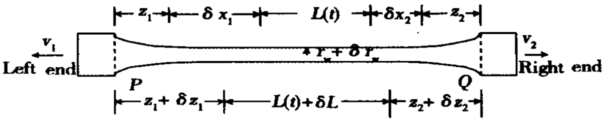

Fig. 3 The tapered waveguide shape at time $t+\delta t$

At time $t+\delta t$, the tapered waveguide shape is shown in Fig. 3. In Fig. 3, δx_1 stands for the increase in left end including the waist; δx_2 the increase in right end including the waist; δz_1 the increased length of the tapered part in the left end; δz_2 the increased length of the tapered part in the right end; δL the variance of the hot－zone; δr_w the variance of the radius of the waist. Obviously, $\delta x_1 = v_1 \delta t$, $\delta x_2 = v_2 \delta t$, $\delta x_2 = (v_2/v_1)\,\delta x_1$. When $\delta t \to 0$, the radius of the waist in the section of δx_1 and δx_2 is approximately equal to $r + \delta r_w$. Thus, according to volume conservation law and mass conservation law regardless of the volume expansion, we have

$$\pi(r_w + \delta r_w)^2 (L(t) + \delta x_1 + \delta x_2) = \pi r_w^2 L(t) \tag{3}$$

Let $\delta x = \delta x_1 + \delta x_2$, we obtain

$$\delta x = (v_1 + v_2)\,\delta t \tag{4}$$

Neglecting the higher order infinitesimal, we obtain

$$2 L r_w\, \delta r_w = - r_w^2\, \delta x \tag{5}$$

Eq. (5) is rewritten for

$$\mathrm{d} r_w / \mathrm{d} x = - r_w / 2L \tag{6}$$

Substituting Eq. (4) into Eq. (6), we have

$$\mathrm{d} r_w / \mathrm{d} t = - [(v_1 + v_2)/2L]\, r_w \tag{7}$$

The variance of the radius r_w of the waist with the time t in the stretching course is shown in Eq. (7).

To keep the waveguide cylindrical, it demands for $\delta L/\delta x \leqslant 1$ or $\delta L/\delta t \leqslant (v_1 + v_2)$. From Fig. 3, we obtain

$$L(t) + \delta L + \delta z_1 + \delta z_2 = L(t) + \delta x_1 + \delta x_2 \tag{8}$$

By simplifying, Eq. (8) is rewritten for

$$\delta z_1 + \delta z_2 = \delta x_1 + \delta x_2 - \delta L \tag{9}$$

Given $\delta L = \alpha\, \delta x_2 = \alpha v_2 \delta t$, where $\alpha \leqslant (v_1 + v_2)/v_2$, so $\delta z_1 + \delta z_2 = (v_1 + v_2 - \alpha v_2)\,\delta t$. Let $\delta z_2 = \beta\, \delta z_1$, we obtain

$$\delta z_1 / \delta t = (v_1 + v_2 - \alpha v_2)/(1+\beta) \tag{10}$$

and

$$\delta z_2 / \delta t = [(v_1 + v_2 - \alpha v_2)/(1+\beta)]\,\beta \tag{11}$$

Using Eqs. (6), (7), (10) and (11), we obtian

$$\mathrm{d} r_w / \mathrm{d} z_1 = - [(v_1 + v_2)(1+\beta)/(v_1 + v_2 - \alpha v_2)]\,[r_w / 2L(t)] \tag{12}$$

When $\delta t \to 0$, $\mathrm{d}L = (\mathrm{d}L/\mathrm{d}t)\,\delta t$, we obtain

$$L(t) = L_0 + \alpha v_2 t \tag{13}$$

where L_0 is the origin length of the hot－zone, and t is the stretched time. Let $K = (v_1 + v_2)(1+\beta)/(v_1 + v_2 - \alpha v_2)$, we have

$$\mathrm{d} r_w / \mathrm{d} z_1 = - \{K/[2(L_0 + \alpha v_2 t)]\}\, r_w \tag{14}$$

Using Eqs. (10), (11) and original condition, that is, z_1 and z_2 are zero when t equals to zero, we obtain

$$z_1 = [(v_1 + v_2 - \alpha v_2)/(1+\beta)]\; t$$

$$z_2 = [(v_1 + v_2 - \alpha v_2)/(1+\beta)]\; \beta t \tag{15}$$

Let $Q_1^{-1} = (v_1 + v_2 - \alpha v_2)/(1+\beta)$, $Q_2^{-1} = [(v_1 + v_2 - \alpha v_2)/(1+\beta)]\,\beta$, we have $z_1 = Q_1^{-1} t$ and $z_2 = Q_2^{-1} t$. By arranging, we have

$$\mathrm{d}r_w/r_w=-\{K/[2(L_0+\alpha v_2Q_1z_1)]\}\,\mathrm{d}z_1 \tag{16}$$

Integrating over the both sides of Eq. (16), we have

$$r_w(z_1)=r_0\exp\left[-\int_0^{z_1}\frac{K}{2(L_0+\alpha v_2Q_1z_1)}\mathrm{d}z_1\right] \tag{17}$$

Similarly,

$$r_w(z_2)=r_0\exp\left[-\int_0^{z_2}\frac{K}{2(\beta L_0+\alpha v_2Q_1z_2)}\mathrm{d}z_2\right] \tag{18}$$

When the hot—zone expansion varies with the pulling velocities in the same ratio in two ends, we have $\beta=v_2/v_1$.

When $v_1=v_2=v$, $\beta=1$. Given $Q=Q_1=Q_2$, $Q^{-1}=(2v-\alpha v)/2$, $K=4/(2-\alpha)$, $\delta x_1=\delta x_2=\delta x/2$, $\delta z_1=\delta z_2=\delta z$, using Eqs. (17), (18) and above expressions, we obtain

$$r_w(z)=r_0\{1+2\alpha z/[(2-\alpha)L_0]\}^{-1/\alpha} \tag{19}$$

In this paper, $\delta L=\alpha\,\delta x_2=\alpha\,\delta x/2$, let $\alpha'=\alpha/2$, we obtain

$$r_w(z)=r_0\{1+2\alpha' z/[(1-\alpha')L_0]\}^{-1/2\alpha'} \tag{20}$$

Obviously, Eq. (20) coincides with Eq. (19) in Ref. [4].

When $\alpha=0$ in Eq. (13), that is, the length of hot—zone remains constant L_0, we obtain

$$K=1+\beta$$

$$Q_1^{-1}=(v_1+v_2/(1+\beta) \qquad Q_2^{-1}=[(v_1+v_2)/(1+\beta)]\,\beta \tag{21}$$

Therefore

$$r_w(z_1)=r_0\exp\{-[(1+\beta)/2L_0]\,z_1\}$$
$$r_w(z_2)=r_0\exp\{-[(1+\beta)/2\beta L_0]\,z_2\} \tag{22}$$

It is observed that, when the length of hot—zone keeps constant, the radii of the two tapered waveguides decrease exponentially. Moreover, the rate of decrease of the radii is only related to the ratio of v_1 to v_2, other than the values of v_1 and v_2. This property can be used for adjusting the taper of the transition. And then we can fabricate the various taper of waveguides by controlling the ratio of the stretching velocities in two ends and the hot—zone length, and further make the various shape of tapered waveguide for 1× N coupler.

When any of v_1 and v_2 equals the zero, assuming $v_2=0$, we obtain

$$r_w(z_1)=r_0\exp[-(2L_0)^{-1}z_1] \tag{23}$$

From Eq. (23), we can draw a conclusion that one decreases exponentially when the other is zero. For an ideal case, the rate of the decrease of the radius, which is not pulled, is infinite at $z_1=0$.

3 Conclusion

In this paper, a model which shows the shape of the tapered waveguide by stretching the rod waveguide in two pulling velocities in two ends in opposite directions is presented. Based on this model, we can conclude that the shape of the tapered waveguide is up to the ratio of the two pulled velocities in the ends and the hot—zone length. It is a foundation on which we can fabricate the desired tapered waveguide for tapered mixing—rod coupler. Furthermore, it is easier to control the ratio of the pulling velocities than to adjust the hot—zone length presented in Ref. [4].

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