Abstract- The performance of optical fiber directional coupler depends upon the material dispersion and the change of temperature. Usually, the directional coupler is designed by assuming that it is used with a specific temperature such as 300°K and a specific wavelength such as 1.55μm. The directional coupler is used with different wavelengths and temperatures than that the specific values. Therefore, with neglect the effect of temperature and change of operating wavelength there are errors in the performance of directional coupler as a power divider (error of output powers), power combiner (error of output powers) and as a bandpass filter (error of passband wavelengths).

The propagation constants of the two fibers and the coupling coefficient between the two fibers are functions of the operating temperature and operating wavelength. The errors for as a power divider (as a combiner) are greater than the error for as a bandpass filter. As the germania ratio increases, the error value increases. Also as the absolute value of the difference between the wavelength and the reference wavelength increases, the error becomes more. Also, this occurs with the temperature. While as the coupler length (L) increases, the error of output power either increases or decreases. These errors can be minimized at certain operating and structure parameters of the optical fiber directional coupler.

Key words: Directional Coupler, coupled mode theory, power divider, bandpass filter, material dispersion

I. INTRODUCTION

The directional coupler is one of the most important component in integrated optic devices [1-4] and their applications still in the new researches [1,3,5]. It consists of two adjacent fibers (waveguides) which separated by very small distance (Fig.1). It has several applications such as power divider, power combiner and bandpass filter.

![Fig.1 Cross section of two symmetrical optical fibers directional coupler](image)

The refractive indices of the two fibers of the directional coupler are functions of wavelength (λ), temperature (T) [6] and germania ratio x, (ratio of germania, GeO2, doped to the silica in the core of fiber) [7]. As the temperature (T °K) increases, both the core refractive index (silica doped germania, n_g) and clad refractive index (pure silica, n_c) are increased. While both n_g and n_c are lowered with wavelength (λ μm). As the germania ratio, x, increases, the refractive index of core increases.

The propagation constants of the two single mode fibers (β_1 and β_2) are determined by using the empirical equation with normalized frequency (V= 1.5 to 2.4) [8,9]. The values of β_1 and β_2 are functions of T and λ.

The coupling coefficient (C) is evaluated by using the coupled mode theory (CMT) [10-12]. In this method the two fibers directional coupler are treated as a two individual waveguides. A general formula for the coupling
coefficient is done. The value of C depends strongly on both the wavelength (\(\lambda\)) and the refractive indices of the two fibers. So, C depends upon material dispersion (MD) [13] and temperature (T).

As the wavelength increases, the coupling coefficient (C) increases but the propagation constant (\(\beta\)) decreases, while vice versa with the effect of temperature.

The input optical power to the directional coupler (P\(_{i}\)) transfers between the two fibers of the directional coupler (P\(_{1}\) and P\(_{2}\)). The values of P\(_{1}\) and P\(_{2}\) are functions of C and \(\Delta\beta\) (where \(\Delta\beta = \beta_1 - \beta_2\)), also on the length of coupler (L). Therefore, P\(_{1}\) and P\(_{2}\) are functions of \(\lambda\) and T. In case of \(\beta_1 = \beta_2\), the input power can be completely transferred from one fiber to another and the output power affects by C and L only.

The performance of optical directional coupler has an error, if the refractive indices of the fibers are considered constant value (which evaluated at reference wavelength, \(\lambda_r = 1.55\mu m\) and reference temperature, \(T_r = 300^\circ K\)) without material dispersion and change of temperature.

The directional coupler can be used as multi windows bandpass filter or reject band filter according to the coupler length.

In this study, the effects of T, MD, x and L on the performance of directional coupler as a power divider and as a bandpass filter are studied with and without the effect of material dispersion and change of temperature.

With neglect the effect of material dispersion and change of temperature, there is a weak error in coupling coefficient (R\(_c\)). This error increases with large values of \(\mid \lambda - \lambda_r \mid\) and \(\mid T - T_r \mid\). But the error in propagation constant (R\(_p\)) is very weak.

The simulation results showed that negligence of the effect of both dispersion and temperature occur very little error at certaines values.

To confirm this concept, a numerical example of two single mode optical fibers directional coupler is studied. The coupler consists of, two symmetrical fibers with core radius (a = 4\(\mu m\)), central to central cores distance (d=10\(\mu m\)), the core material from silica doped germania (with germania ratio, x= 0.025), clad material from pure silica and the coupler length L = 500\(\mu m\).

II. MATHEMATICAL ANALYSIS

II.1. Refractive index, normalized frequency, radius of fiber and coupling coefficient

II.1.1 Refractive indices (\(n_s\) and \(n_c\)), material dispersion (MD) and normalized frequency (V)

Effect of temperature (T), germania ratio (x) and wavelength (\(\lambda\)) on the refractive indices of core (silica doped germania, \(n_{s}\)) and clad (pure silica, \(n_{c}\)) of fiber are defined as [6];

\[
\begin{align*}
\frac{n^2}{s} & = 1 + \frac{a_1t^2d^2}{(\lambda^2 - b_{1xt}^2)} + \frac{a_2t^2d^2}{(\lambda^2 - b_{2xt}^2)} + \frac{a_3t^2d^2}{(\lambda^2 - b_{3xt}^2)} \quad (1.a) \\
\frac{n^2}{c} & = 1 + \frac{a_1t^2d^2}{(\lambda^2 - b_{1xt}^2)} + \frac{a_2t^2d^2}{(\lambda^2 - b_{2xt}^2)} + \frac{a_3t^2d^2}{(\lambda^2 - b_{3xt}^2)} \quad (1.b)
\end{align*}
\]

where;

\[
\begin{align*}
a_{1xt} & = (a_{10} + u_1x) f_{t1}, & a_{2xt} & = (a_{20} + u_2 x) f_{t2}, & a_{3xt} & = (a_{30} + u_3 x) f_{t3}, & b_{1xt} & = (b_{10} + v_1 x) f_{t1}, & b_{2xt} & = (b_{20} + v_2 x) f_{t2}, & b_{3xt} & = (b_{30} + v_3 x) f_{t3} \\
b_{10} & = 0.0684043, & b_{20} & = 0.1162414, & b_{30} & = 9.8961610, & u_1 & = 0.1107001, & u_2 & = 0.31021588, & u_3 & = -0.04331091, & v_1 & = 0.000568306, & v_2 & = 0.03772465, & v_3 & = 1.94577, & f_{t1} & = e_1 + e_2 T, & f_{t2} & = T_0/T, & e_1 & = 0.93721, & e_2 & = 0.0002143, & T_0 & = 293 \, ^\circ K
\end{align*}
\]

\(a_{1}, a_{2}, a_{3}, b_{1}, b_{2},\) and \(b_{3}\) are defined by putting the value of \(x=0\) through the parameters \(a_{1xt}, a_{2xt}, a_{3xt}, b_{1xt}, b_{2xt}\) and \(b_{3xt}\) respectively. wavelength (\(\lambda, \mu m\)) and temperature (T °K).

Note that, the values of \(a_{1xt}, a_{2xt}, a_{3xt}, b_{1xt}, b_{2xt}\) and \(b_{3xt}\) (with \(x=0\) and \(f_{t1}=f_{t2}=1\)) are defined at temperature \(T=293 \, ^{\circ} K\) [14] and so, the best reference temperature \(T_0=293 \, ^{\circ} K\).

The refractive indices of core (\(n_s\)) and clad (\(n_c\)) materials are increase with both temperature (T) and germania ratio (x) while they are decrease with wavelength (\(\lambda, \mu m\)) (Fig.2). Therefore, material dispersion \(\text{MD} = (-\lambda / \nu)(d^2n_s/\lambda^2)\), \(\nu\) is the speed of light) must be taken at the design of directional coupler.

The normalized frequency (V) is defined below (Eq.3). As \(\lambda\) increases, the value of V decreases, while vice versa for T and x (Fig.3).
II.1.2 Limits of fiber core radius (a) and germania ratio (x) for single mode fiber.

For single mode optical fiber with normalized frequency (V ranges between 1.5 and 2.4) and with \( \lambda = 1.5 \) to \( 16 \) \( \mu \)m, \( T = 253 \) to \( 333 \) oK and the GeO_2 ratio, \( x = 2.5 \) to \( 4.0\% \), the corresponding value of core radius \( a = 3.69 \) to \( 4.37 \) \( \mu \)m (We take \( \lambda = 4 \) \( \mu \)m).

II.1.3 Coupling coefficient

The coupling coefficient (C) of two symmetric single mode fibers directional coupler is derived by using coupled mode theory (CMT) [10-12] as;

\[
C = \lambda \frac{1-b}{2 \pi a^2 N} \frac{K_0(\sqrt{V} d_1)}{K_1(\sqrt{V}b)}
\]  
(2)

Where,

\( d_1 = d/a, a \) is the fiber core radius, \( d \) is the distance between two centers and \( V \) is the normalized frequency,

\[
V = \frac{2 \pi}{\lambda} (n_g^2 - n_s^2)^{0.5}
\]  
(3)

\( b \) is the normalized propagation constant,

\[
b = \left( \frac{N^2 - n_s^2}{n_g^2 - n_s^2} \right)
\]  
(4)

\( N \) is the effective refractive index of fiber, propagation constant \( \beta = \frac{2 \pi N}{\lambda} \)  
(5)

\( n_g \) is the core refractive index and \( n_s \) is the clad refractive index  
\( \lambda \) is the operating wavelength, \( K_0 \) and \( K_1 \) are the Bessel functions.

The coupling coefficient \( C \) has a peak value at main value of normalized frequency (\( V_{pc} \)) which affected by the values of \( T \) and \( \lambda \). The value of \( C \) either increases or decreases with temperature \( T \) and \( \lambda \) according to the value of \( V < V_{pc} \) or \( V > V_{pc} \).

II.2 Applications of directional coupler

II.2.1 Directional coupler as a power divider

The input optical power (P_i) through fiber 1 is divided into output power from fiber 1 (P_{o1 div}) and output power from fiber 2 (P_{o2 div}) (Fig.4).

And with lossless symmetric fibers (\( \Delta \beta = \beta_1 - \beta_2 = 0 \)) P_{o1 div} and P_{o2 div} are defined as [15];

\[
P_{o2 \ div} = P_i \sin^2(C \ L)
\]  
(6.a)

\[
P_{o1 \ div} = P_i \cos^2(C \ L)
\]  
(6.b)

Where, \( L \) is the coupler length.
The effect of both temperature (T) and material dispersion (MD) on the output powers \( (P_{o1\ div} \ and \ P_{o2\ div}) \) is evident through C.

II.2.2 Directional coupler as a combiner

The two input optical powers, through fiber 1 \( (P_{i1}) \) and through fiber 2 \( (P_{i2}) \) are combined and the output power from fiber 1 \( (P_{o1\ comb}) \) or output power from fiber 2 \( (P_{o2\ comb}) \) (Fig.5).

And with lossless symmetric fibers \( (\Delta \beta = \beta_1-\beta_2 = 0) \) \( P_{o1\ comb} \) and \( P_{o2\ comb} \) are defined by using coupled wave equations [10,16] as;

\[
P_{o1\ comb} = P_{i1} \cos^2(C\ L) + P_{i2} \sin^2(C\ L) \tag{7.a}
\]
\[
P_{o2\ comb} = P_{i1} \sin^2(C\ L) + P_{i2} \cos^2(C\ L) \tag{7.b}
\]

Where, \( L \) is the coupler length

Also, as in case of directional coupler as a divider, the effect of both T and MD on the output powers \( (P_{o1} \ and \ P_{o2}) \) is evident through C.

II.2.3 Directional coupler as a bandpass filter

The output powers \( (P_{o1} \ and \ P_{o2}) \) are functions of C, so they are functions of \( \lambda \) to degree it acts as a bandpass filter (Fig.6).

The value of bandpass wavelengths \( (\Delta \lambda) \) is defined as [17,18];

\[
\Delta \lambda = 2.5/\left\{L \left| \frac{dC}{d\lambda} \right| \right\} \tag{8}
\]

Where, \( L \) is the directional coupler length

The effect of both temperature and material dispersion on \( \Delta \lambda \) is evident through \( dC/d\lambda \).

II.3 Errors due to neglect the effect of either T or MD or both T and MD

\( \beta_{MD} \), \( C_{T\ MD} \), \( P_{2\ div\ r\ MD} \), \( P_{2\ comb\ r\ MD} \) and \( \Delta \lambda_{T\ MD} \) are the values of \( \beta \), \( C \), \( P_{2\ div} \), \( P_{2\ comb} \) and \( \Delta \lambda \) with \( n_g \) and \( n_s \) at \( \lambda_e = 1.55\mu m \).

\( \beta_{T} \), \( C_{T} \), \( P_{2\ div\ r\ T} \), \( P_{2\ comb\ r\ T} \) and \( \Delta \lambda_{T\ T} \) are the values of \( \beta \), \( C \), \( P_{2\ div} \), \( P_{2\ comb} \) and \( \Delta \lambda \) with \( n_g \) and \( n_s \) at \( T_r = 300^\circ K \).

\( \beta_{T\ MD} \), \( C_{T\ MD} \), \( P_{2\ div\ r\ T\ MD} \), \( P_{2\ comb\ r\ T\ MD} \) and \( \Delta \lambda_{T\ T\ MD} \) are the values of \( \beta \), \( C \), \( P_{2\ div} \), \( P_{2\ comb} \) and \( \Delta \lambda \) with \( n_g \) and \( n_s \) at \( \lambda_e = 1.55\mu m \) and \( T_r = 300^\circ K \).

II.3.1 Error due to neglect the effect of material dispersion (i.e. refractive index evaluated at \( \lambda_e = 1.55\mu m \)) are;

\[
R_{\beta\ MD\ %} = 100 \frac{\beta\ at\ any\ \lambda - \beta_{MD\ %}}{\beta\ at\ any\ \lambda} \tag{9.a}
\]
\[
R_{C\ MD\ %} = 100 \frac{C\ at\ any\ \lambda - C_{MD\ %}}{C\ at\ any\ \lambda} \tag{9.b}
\]
\[
R_{P_{2\ div\ MD\ %}} = \frac{P_{2\ div\ at\ any\ \lambda} - P_{2\ div\ r\ MD\ %}}{P_{2\ div\ at\ any\ \lambda}} \tag{9.c}
\]
\[
R_{P_{2\ comb\ MD\ %}} = 100 \frac{P_{2\ comb\ at\ any\ \lambda} - P_{2\ comb\ r\ MD\ %}}{P_{2\ comb\ at\ any\ \lambda}} \tag{9.d}
\]
\[
R_{\Delta\lambda\ MD\ %} = 100 \frac{\Delta\lambda\ at\ any\ \lambda - \Delta \lambda_{MD\ %}}{\Delta\lambda\ at\ any\ \lambda} \tag{9.e}
\]

II.3.2 Error due to neglect the effect of varying temperature from \( (T_r = 300^\circ K) \) are;

\[
R_{\beta\ T\ %} = \frac{\beta\ at\ any\ T - \beta_{T\ %}}{\beta\ at\ any\ \lambda} \tag{10.a}
\]
\[
R_{C\ T\ %} = 100 \frac{C\ at\ any\ T - C_{T\ %}}{C\ at\ any\ T} \tag{10.b}
\]
\[
R_{P_{2\ div\ T\ %}} = 100 \frac{P_{2\ div\ at\ any\ T} - P_{2\ div\ r\ T\ %}}{P_{2\ div\ at\ any\ T}} \tag{10.c}
\]
II.3.3 Error due to neglect both MD ($\lambda \neq \lambda_r$) and T ($T\neq T_r$) are; 
\[ R_{\beta T MD} \% = 100 \frac{\beta_r T}{\beta T} \]  
(11.a)
\[ R_C T MD \% = 100 \frac{C_r T}{C T} \]  
(11.b)
\[ R_{P2div T MD} \% = 100 \frac{P2div_r T}{P2div T} \]  
(11.c)
\[ R_{P2comb T MD} \% = 100 \frac{P2comb_r T}{P2comb T} \]  
(11.d)
\[ R_{\Delta \lambda T MD} \% = 100 \frac{\Delta \lambda_r T}{\Delta \lambda T} \]  
(11.e)

III. SIMULATION RESULTS and DISCUSSIONS

From (Fig.7.a), as the temperature increases, C decreases with $\lambda=1.50$ and 1.55$\mu$m (where $V> V_{pc}$) while C increases with $\lambda = 1.6\mu$m (where $V<V_{pc}$). From (Fig.7.b), the percentage error of the coupling coefficient ($R_C$) due to varying temperature from 300ºK, increases with $\Delta T$ ($\Delta T_{300} = \text{abs}(T-300)$) and maximum percentage error ($R_{C max}$) = 3.3459 at $T=252$ºK with $\lambda=1.50\mu$m.

For the two optical fiber directional coupler with $\beta_1 = \beta_2$, the output power ($P_{o2 div}$) depends upon the value of C and the coupler length (L). $P_{2div}$ depends upon both $T$ and $\lambda$ (Fig.7.c). Maximum percentage error of $P_{o2 div}$ ($R_{P2 max}$) is 5.9328 occurs at $T=252$ and $\lambda=1.50\mu$m (Fig.7.d).

The passband wavelength ($\Delta \lambda$) decreases with $\lambda$ and T (Fig.7.e) and the percentage error of passband wavelength ($R_{\Delta \lambda}$) increases with $\lambda$ {maximum percentage error, for $T=252$ ºK, $R_{\Delta \lambda max} = 1.1254$ (at $\lambda= 1.50\mu$m), 0.2213 (at $\lambda=1.55\mu$m) and 0.2275 (at $\lambda= 1.60\mu$m)} (Fig.7.f).

As expected, coupling coefficient increases with $\lambda$ (Fig.8.a) where $V < V_{p}$, dependence of C on T weakly. The corresponding percentage error ($R_C$ ) due to neglect the material dispersion of core and clad materials of fiber ($R_{C\lambda1.55}$) increases with the value of $\text{abs}(\lambda-1.55)$ (Fig.8.a and Fig.8.b).
The error due to neglect the effect of temperature (T≠ T_r =300°K) and neglect the material dispersion (refractive index evaluated at λ_r=λ=1.55μm only) increases with λ for R_c, R_p2 and R_Δλ (Fig.8). The value of Δλ decreases with both λ and T (Fig.8(e)).

Coupling coefficient decreases with germania ratio (x) (Fig.9.a) (because core refractive index increases and so C decreases) the value of R_c increases with x (Fig.9.b). With directional coupler length L=0.5 mm, the output power P_o2_div decreases with x. Also Δλ decreases with x and λ (Fig.9.e). The values of C, P_o2_div and Δλ are decreased with x and T (Figs.10.a, 10.c and 10.e) and vice versa for R_c and R_p2_div (Figs.10.b and 10.d).

- The error due to neglect the effect of temperature (T≠ T_r =300°K) and neglect the material dispersion (refractive index evaluated at λ=λ_r=1.55μm only) increases with λ for R_c, R_p2 and R_Δλ (Fig.8). The value of Δλ decreases with both λ and T (Fig.8(e)).

- Coupling coefficient decreases with germania ratio (x) (Fig.9.a) (because core refractive index increases and so C decreases) the value of R_c increases with x (Fig.9.b). With directional coupler length L=0.5 mm, the output power P_o2_div decreases with x. Also Δλ decreases with x and λ (Fig.9.e).

- The values of C, P_o2_div and Δλ are decreased with x and T (Figs.10.a, 10.c and 10.e) and vice versa for R_c and R_p2_div (Figs.10.b and 10.d).

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**Fig.8** Effect of neglect material dispersion on the performance of directional coupler (with L=500μm, a=4μm, d=10μm, x=0.025)

- **(a)**
- **(b)**
- **(c)**

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**Fig.9** Effect of GeO_2 ratio (x) and λ on the performance of directional coupler (with T=300°K, L=500μm, a=4μm, d=10μm)
Fig. 10: Effect of GeO$_2$ ratio ($x$) and temperature ($T$) on the performance of the directional coupler (with $\lambda=1.55\mu m$, $L=500\mu m$, $a=4\mu m$, $d=10\mu m$).

As the difference ($T-T_r$) increases, the percentage error of propagation constant ($R_\beta T_\lambda$) becomes evident increases, while the error due to ignore the material dispersion is little (Fig. 11.a).

Percentage error of $C$ ($R_C$) increases with abs ($\lambda-\lambda_r$) with speed rate, while the effect of $T$ very little (Fig. 11.b). Percentage error of $P_{o2\ div}$ ($R_{P2\ div}$, Fig. 11.c) similar with error of $C$ (Fig. 11.b).

But the percentage error of $\Delta \lambda$ (Fig. 11.d) either increases or decreases with $T$ and $\lambda$ due to the $\Delta \lambda$ in relation with $dC/d\lambda$.

As the germania ratio increases, the error increases (Figs. 11 and 12). Such as percentage error of $P_{o2\ div}$ ($R_{P2\ div}$) increases from 4.6 (with $x=0.025$) to 11.32 (with $x=0.04$).

The percentage error of the output power ($R_{P2\ div}$) either increases or decreases with the coupler length ($L$) (Fig. 13). The temperature dependence of $R_{P2}$ very little, while the wavelength dependence of $R_{P2\ div}$ increases with absolute ($\lambda-\lambda_r$) increases with temperature.

Fig. 11: Percentage errors of propagation constant ($R_\beta$), coupling coefficient ($R_C$), output power ($R_{P2\ div}$) and bandwidth ($R_\Delta \lambda$) due to neglect both MD and $T$. With $x=0.025$, $L=500\mu m$, $a=4\mu m$, and $d=10\mu m$. ($T_r=300^\circ K$ and $\lambda_r=1.55\mu m$).
Fig. 12: Percentage errors of propagation constant ($R_{β}$), coupling coefficient ($R_{C}$), output power ($R_{P2 div}$) and bandwidth ($R_{Δλ}$) due to neglect both MD and T. With $x=0.04, L=500 \mu m, a=4 \mu m$, and $d=10 \mu m$ ($T_r=300^\circ K$ and $λ_r=1.55 \mu m$).

Fig. 13: Effect of coupler length ($L$) on the percentage error of $P_2$ ($R_{P2 div}$).

From Fig. 14.a, the value of bandpass ($Δλ$) decreases with $T$, where the value of $P_{o2 \ div}$ increases with $T$. With different $L$, the directional coupler can act as band rejected (Fig. 14.b) or multi passbands (Fig. 14.c).

As expected the number of bandpass windows increases with the coupler length (Fig. 15). The passband ($Δλ$) decreases with $T$ (Table 1). The peak of $P_{o2 \ div}$ crawls toward the high wavelength (Table 1). The number of passband windows and the rejected widow depend upon the coupler length (Figs 10 and 11). The values of passband ($Δλ_p$) and rejected band ($Δλ_R$) are decreased with increasing the operating temperature (Table 2).
Fig. 15 Effect of L on the performance of directional coupler as a bandpass filter with different coupler length L.

(With \( x=0.025 \), \( a=4\mu m \), and \( d=10\mu m \))

Table 1: Effect of temperature on the band wavelengths of the directional coupler as a bandpass filter

<table>
<thead>
<tr>
<th>T °K</th>
<th>( \lambda_{h1} ) (P=1/2 ( P_{max} )) nm</th>
<th>( \lambda_{h1} ) (P=( P_{max} )) nm</th>
<th>( \lambda_{h1} ) (P=1/2 ( P_{max} )) nm</th>
<th>( \Delta \lambda ) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>1512.83</td>
<td>1537.30</td>
<td>1564.06</td>
<td>52.23</td>
</tr>
<tr>
<td>273</td>
<td>1513.44</td>
<td>1537.70</td>
<td>1563.99</td>
<td>50.55</td>
</tr>
<tr>
<td>300</td>
<td>1514.33</td>
<td>1538.20</td>
<td>1563.90</td>
<td>49.57</td>
</tr>
<tr>
<td>333</td>
<td>1515.53</td>
<td>1538.80</td>
<td>1563.84</td>
<td>48.31</td>
</tr>
</tbody>
</table>

Table 2: Effect of temperature on the band wavelengths of the directional coupler as a bandpass filter

(\( a=4\mu m, d=10\mu m, L=40mm, x=2.5\% \)) as shown in Fig. 16.a

<table>
<thead>
<tr>
<th>T °K</th>
<th>( \lambda_{h1} ) (P=1/2 ( P_{max} )) nm</th>
<th>( \lambda_{h1} ) (P=( P_{max} )) nm</th>
<th>( \lambda_{h1} ) (P=1/2 ( P_{max} )) nm</th>
<th>( \Delta \lambda ) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta \lambda_{F1} )</td>
<td>( \Delta \lambda_{R} )</td>
<td>( \Delta \lambda_{F2} )</td>
<td>( \Delta \lambda_{F1} )</td>
</tr>
<tr>
<td>253</td>
<td>23.61</td>
<td>25.51</td>
<td>28.18</td>
<td>25.51</td>
</tr>
<tr>
<td>273</td>
<td>23.38</td>
<td>25.21</td>
<td>27.63</td>
<td>25.21</td>
</tr>
<tr>
<td>300</td>
<td>23.01</td>
<td>24.70</td>
<td>26.90</td>
<td>24.70</td>
</tr>
<tr>
<td>333</td>
<td>22.53</td>
<td>24.06</td>
<td>26.00</td>
<td>24.06</td>
</tr>
</tbody>
</table>

From Fig.16.a, the value of bandpass (\( \Delta \lambda \)) decreases with T (Fig.8.a, Fig.11.a), where the value of \( P_{2} \) increases with T. With different L, the directional coupler can acts as band rejected (Fig.16.b) or multi passbands (Fig.15.c, Fig.16.b).
The combiner output is periodically with wavelength and increases with temperature (Fig. 17.a) The error due to neglect change of temperature increases with $\Delta T$ (Fig.17.b) but error increases or decreases with $\lambda$.

![Image](https://example.com/image1.png)

a) combiner output  
b) error in combiner due to $T$ and $\lambda$

**Fig.17** Directional coupler as a combiner ($P_{i1}$=0.5, $P_{i2}$=1.5), $L=30$mm

**IV. CONCLUSION**

The performance of optical directional coupler depends upon both the material dispersion (MD) of fiber and the change of temperature ($\Delta T$). The error due to neglect MD increases with the absolute difference between the operating wavelength ($\lambda$) and the reference wavelength ($\lambda_r=1.55\mu m$). Also the error due to neglect $\Delta T$ increases with the difference between the operating temperature ($T$) and the reference temperature ($T_r=300^\circ K$).
The error of propagation constant of the fiber ($\beta$) is very little. But the error of the coupling coefficient between two fibers (C) becomes evident. While the errors of output power for divider ($P_{o2\text{ div}}$) and for combiner ($P_{o2\text{ comb}}$) also the error of passband ($\Delta \lambda$) of the bandpass filter are varying periodically from small to large and vice versa according to the coupler length ($L$) and the wavelength ($\lambda$).
The error becomes more with the ratio of GeO$_2$ in the fiber core. At $T=300^\circ K$, the error of $P_{o2}$ with $x=4\%$ becomes 30 times of error with $x=2.5\%$. Also, at $T=333^\circ K$, the error of $\Delta \lambda$ with $x=4\%$ becomes 14 times of error with $x=2.5\%$.
The errors can be minimized by use certain operating and structure parameters of the directional coupler. The effect of $T$ and DM must be taken into account when using the directional coupler.

**V. REFERENCES**

[1] Rongqing Hui, "Fiber Directional Coupler," ScienceDirect, Copyright © 2022 Elsevier B.V. or its licensors or contributors. ScienceDirect ® is a registered trademark of Elsevier B.V. Copyright © (2022).  

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