Mechanical means for temperature compensation of planar diffractive optical interconnects: feasibility study

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Abstract. Planar diffractive optical interconnects have many advantages, however, their inherent chromaticity leads to temperature instability due to the wavelength shift of laser diodes’ radiation. This shift can be compensated if the optical interconnect is bended in an appropriate direction with curvature proportional to the relative wavelength shift. The bending can be performed by attaching an additional plate to the element with a different thermal expansion coefficient. Theoretical analysis and ray tracing are reported.

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In the semiconductor industry, there is a continually aggravating problem of increasing communication volume. Optical interconnection technology is seen as a prime option for solving this problem. In planar optical interconnects (POI) light is injected (by an in-coupling optical element) into a transparent slab (light guide) at a total internal reflection angle (θ in Fig. 1) and propagates along it until it meets an out-coupling optical element and goes to the detector. Diffractive lenses as coupling optical elements have many advantages and have been suggested also in the context of quasi-optics for rapidly expanding terahertz technology. However, their intrinsic dependence of optical properties on the wavelength—chromaticity—poses difficult problems. Chromaticity leads also to temperature instability. Namely, the wavelength of semiconductor lasers is temperature-dependent. Temperature change causes wavelength shift, therefore the laser beam as deflected by the diffractive in-coupling optical element deviates from its desired path and can miss the out-coupling element. For example, for a typical 850-nm vertical-cavity surface-emitting lasers (VCSEL) source the wavelength shift is \( d\lambda/dT = 0.06 \text{ nm/K} \), i.e., relative wavelength shift is \( (1/\lambda)(d\lambda/dT) \approx 7 \times 10^{-5} \text{ K}^{-1} \). If POI was assembeled at 20°C, the working temperature is 140°C (Max3905 from Dallas Semiconductors, e.g.), and the POI length is 10 cm, the resulting beam deviation is about 1.7 mm (see below the calculation). This temperature instability is specific for diffractive POI since other thermal effects are much less:

\[ \frac{\Delta l}{l} = \frac{\tan \psi - \tan \psi}{\tan(\psi)} \]

let us consider the problem quantitatively. At some reference temperature \( t_0 \), POI is strictly planar and the incident angle of the incoming beam is zero (Fig. 1). Let the propagation angle (within POI) be \( \psi \) (see Fig. 1). When temperature changes \( t \), POI bends symmetrically in respect to perpendicular plane situated just in the middle between the input and output diffractive elements (Fig. 2). The incident angle \( \alpha \) becomes nonzero since the laser beam direction does not change in the lab frame. However, the bending curvature can be tuned in such a way that the propagation angle \( \psi \) retains its original value (locally in the incidence/refraction point) due to the incident angle change. We show now how this tuning is achieved.

First, we derive the beam displacement as function of wavelength \( \lambda \). For the reference radiation wave vector \( k_0 = 2\pi/\lambda_0 \), incident angle \( \alpha_0 = 0 \), grating vector \( K = 2\pi/\Lambda \) (\( \Lambda \) is grating period), propagation angle \( \psi \), and propagation vector \( \vec{r} \) we have

\[ r_x = K \sin \psi = r_x/k_0 = K/k_0 = \lambda_0/n\Lambda \]

[see Fig. 3(a)]. For another wavelength (wave vector \( k \)), the propagation angle \( \psi' \) is different [Fig. 3(b)]. We define relative beam displacement as \( \Delta l/l = (\tan \psi' - \tan \psi)/\tan(\psi) \), since in one “period” (bounce-back) the

![Fig. 1 Planar optical interconnect layout. Initial (thick line) and displaced due to the laser-wavelength-shift (thin line) beams are shown.](image-url)
beam covers longitudinal distance \( l = 2d \tan \psi \) (Fig. 1), where \( d \) is the light guide thickness. We suppose that the relative displacement is rather small and consider equal numbers of “periods.” To calculate this relative displacement, we define the wavelength relative change as

\[
\delta = (k - k_0)/k_0 \approx (\lambda - \lambda_0)/\lambda_0,
\]

where \( \delta \) is defined as positive for shorter wavelengths (longer wave vectors) in respect to the basic one at reference temperature \( T_0 \). Calculation of relative beam displacement in the first order in respect to \( \delta \) yields:

\[
d(tan \psi)/d\lambda = [d(tan \psi)/d(sin \psi)] [d(sin \psi)/d\lambda].
\]

As for the second term, we have from Eq. (1) \( d(sin \psi)/d\lambda = 1/n\lambda \), and for the first one \( d(tan \psi)/d(sin \psi) = d(tan \psi)/d\psi \cdot d(sin \psi)/d\psi \), yielding finally

\[
\frac{\Delta l}{l} \approx \frac{\Delta \lambda}{\lambda \cos^2 \psi}.
\]

Since usually \( \psi \sim \pi/4 \), \( \Delta l/l \approx 2\delta \). For example, taking the relative wavelength shift \((1/\lambda)(d\lambda/dT) \sim 7 \cdot 10^{-5} \text{ K}^{-1}\) (for 850-nm VCSEL, as mentioned above) and temperature shift \( 120^\circ \text{C} \), we get \( \Delta l/l \approx 0.017 \), i.e., for \( L = 100 \text{ mm} \), \( \Delta L = L \cdot \Delta l/l = 1.7 \text{ mm} \).

In order to correct this deviation we want to get the same propagation angle \( \psi \) at a different temperature \( T \). To achieve this we must take nonzero incident angle \( \alpha \) [Fig. 3(c)]. Therefore \( r' = K + k \sin \alpha \) and \( \sin \psi = r'/nk \). We obtain

\[
\frac{K}{nk_0} = \frac{K + k \sin \alpha}{nk}.
\]

Substituting Eq. (1) into this equation and making use of \( \delta \) defined in Eq. (2) yields

\[
\sin \alpha = \frac{(\delta(1 + \delta)) n \sin \psi}{e = 2d\alpha/L},
\]

where \( \alpha \) is given by Eq. (5), \( e \) is defined as \( e = d/R \), and \( d \) is the POI thickness. Positive values of dimensionless curvature \( e \) and radius \( R \) correspond to curvature center from the laser/detector side (see Fig. 2).

Let us calculate now the change of the beam trajectory in the curved element with respect to the original planar. Consider one beam reflection. In Fig. 4, \( E\hat{A}O = \pi - \psi \). In the triangle \( \triangle EAO \), \( E\hat{A}O = \pi - (\pi - \psi) - \beta = \psi - \beta \) (it should be noted here that the second incidence angle \( A\hat{E}O \) is smaller than \( \psi \) and can be below the total internal reflection threshold). In \( \triangle EBA \), \( \tan(\psi - \beta) = AB/EB \). Considering circumference with origin \( O \) we get \( EB = EC + CB = d + R(1 - \cos \beta) \) and \( AB = R \sin \beta \). We have therefore

\[
\Delta l/l \approx \frac{\Delta \lambda}{\lambda \cos^2 \psi}.
\]
\[ d + R (1 - \cos \beta) = R \sin \beta \cdot \cot(\psi - \beta) \]  \hspace{1cm} (7)

and finally
\[ \epsilon + 1 - \cos \beta = \sin \beta \cot(\psi - \beta). \]  \hspace{1cm} (8)

We solve this equation by iterations, supposing that for small \( \epsilon, \beta \) will be also small. Expanding Eq. (8) in respect to \( \beta \) and keeping the leading term only, we have
\[ \beta_1 = \epsilon \tan \psi. \]  \hspace{1cm} (9)

Within this approximation, the distance between input and output of 1 bounce-back is \( 2R\beta_1 = 2R(d/dL)\tan \psi = 2d \tan \psi \), exactly as in the planar case (Fig. 1). Though the actual beam deviation in space is nonzero due to the bending, it is of second order in respect to \( \delta \). However, actually there is linear with \( \delta \) deviation. In order to estimate it, we make the second iteration. Substituting \( \beta = \beta_1 + \beta_2 \) and keeping the leading order of \( \beta_2 \) yields
\[ \beta_2 = -\frac{3 + \cos 2\psi}{2 \sin 2\psi} \beta_1. \]  \hspace{1cm} (10)

As mentioned above, the unperturbed input-output distance is \( l = 2d \tan \psi = 2R\beta_1 \), and after wavelength shift and correction bending this distance is \( 2R(\beta_1 + \beta_2) \). So the first order approximation to the relative beam displacement is
\[ \frac{\Delta l}{l} = \frac{\beta_2}{\beta_1} = -\frac{3 + \cos 2\psi}{2 \sin 2\psi} \tan \psi. \]  \hspace{1cm} (11)

Thus \( \Delta l/l \sim \delta - d/dL \) [Eqs. (5) and (6)].

Without bending, as mentioned before [Eq. (3)], the relative beam displacement is \( \Delta l/l \sim 2\delta \). Therefore the wavelength-shift-caused beam deviation is reduced by factor of \( \sim d/dL \), i.e., usually above one order of magnitude.

Figure 5 presents ray tracing results of the beam deviation of second order in respect to beam deviation in space is nonzero due to the bending, it is of second order in respect to \( \delta \). However, actually there is linear with \( \delta \) deviation. In order to estimate it, we make the second iteration. Substituting \( \beta = \beta_1 + \beta_2 \) and keeping the leading order of \( \beta_2 \) yields
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Figure 5 presents ray tracing results of the beam deviation as function of wavelength change—with and without compensation by means of POI bending. Exact ray tracing [numerical solution of Eq. (8)] results are indistinguishable from the approximation [Eq. (11)].

The proposed scheme works only when the source and the detector are situated from one side of POI, but this seems to be the common case. One can realize this scheme for rectangular or circular arrays of sources/detectors. In the latter case, each pair source-detector should be situated diametrically and the bending curvature center should be at the line normal to the array circle and crossing its center. Linear behavior of curvature in respect to temperature should take place also in this case.

Finally, speaking about diffractive optical elements for VCSEL, it should be mentioned that there is an unavoidable spread of nominal VCSEL wavelengths (at a given temperature) from one laser array (chip) to another of usually up to around 10 nm or more. The problem of this “bias” may be solved at the assembling stage by off-axis adjusting of the laser array, as in Fig. 3(c). The off-axis angle \( \alpha \) is given by Eq. (5); its magnitude is about \( \alpha - \Delta \lambda/\lambda \sim 0.01 \). As far as \( \epsilon \ll 1 \), the effects are linear and this adjusting should not affect the above results regarding the temperature compensation.

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References