Chapter 3

Principle of Optical Waveguide Alignment and UV Writing

Following the brief review on silica waveguides in Chapter 2, we now turn our attention to waveguide alignment. The end-product of an alignment process for waveguides is the ‘gluing’ of input and output optical fiber(s), also known as pigtailing. This is a labor intensive, low throughput process. As such, the ability to improve, and possibly automate alignment, is an important area of research.

3.1: Optical Waveguide Alignment

Optical waveguide alignment is the approach to achieve maximum intensity of optical signal at the output of device under test (integrated optical chip) with 1% of noise contribution to the peak value [1]. A ‘poorly aligned’ waveguide will suffer from high loss on the transmitted optical signal. Optical waveguide alignment is more likely a hide-and-seek game in a stringent environment [2]. Naturally, the harsh condition is inherent from the design of waveguide where the wave guiding structure within the waveguide is in mirco-meter scale and is not visible for naked eye. Hence, high quality of alignment is a must for optical waveguides as it maximizes the power throughput of any waveguides related applications or technologies.

Traditionally, optical devices/waveguides packaging is normally performed by trained personnel with the assistance of microscope and ultra precision stages [3], this process tends to be time consuming as efforts are required to seek for the input channel.

So, this process contributes largest portion to the overall process cost [1, 4]. Though the alignment quality or procedure is improving from time to time, the progression is still slow. For example, machine vision system is now commercially available for the device alignment, yet there are still rooms available for embedded intelligence system to improve [5-7].

A fully characterized device is a device which has been characterized according to the applicable aspects such as insertion loss and optical return loss. Regardless of the measurements chosen, these values are only reliable whenever the coupling efficiency of optical waveguide has been achieved. If such criterion is failed to fulfill, a factory standard fabricated optical waveguide remains “silence”, and therefore reduces the waveguide popularity indirectly.

3.1.1: Principle of Waveguide Alignment

The concern of any waveguide alignment will be the coupling efficiency, Γ, which is defined by the overlap integral of the excitation field, ε, and the waveguide field, E, in the core region [8, 9] where the integral of two fields is given by Eqn. 3.1 [8].

$$\Gamma = \frac{\int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} E\varepsilon dx}{\left[\int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} E^2 dx \bullet \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} \varepsilon^2 dx\right]^{\frac{1}{2}}} \qquad \text{(Eqn. 3.1)}$$

The denominator of eqn. 3.1 represents the normalizing factor, and the value of Γ varies from 0 to 1 which corresponded to no coupling and total coupling due to field overlapping [8]. Practically, this equation is normally used with fundamental mode field which is guided inside the core region of the waveguide; yet it is also applicable to other modes fields that are being guided by the core region [8]. Fig. 3.1 illustrates the situation of waveguide alignment and Fig. 3.2 shows the overlapping of two fields with Gaussian distribution profile.

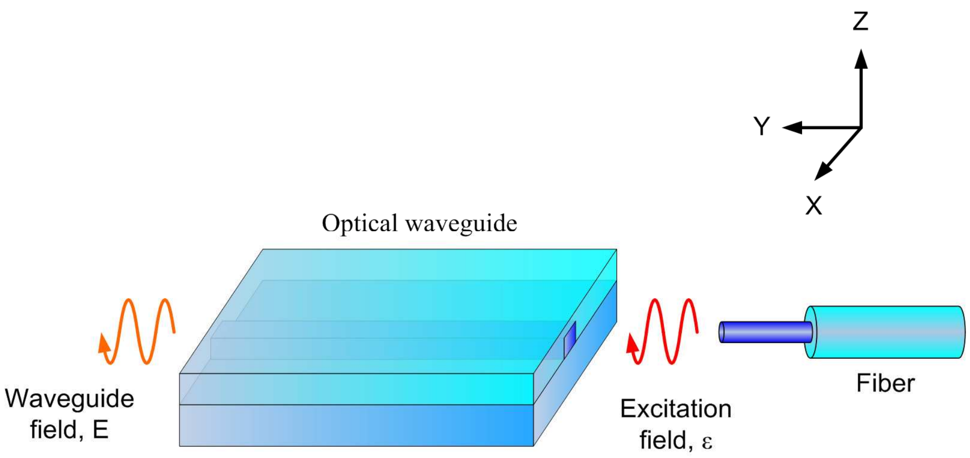

Fig. 3.1: Waveguide alignment.

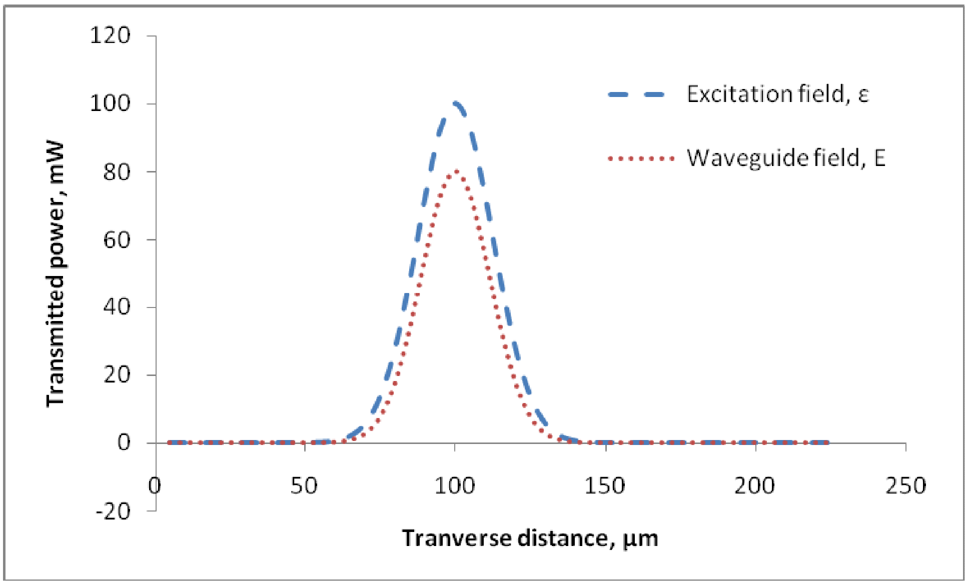

Fig.3.2: Field overlapping between excitation and waveguide field.

In optical device alignment, it is typical to couple a Single Mode Fiber (SMF) with a waveguide. Hence, the field distribution of the incident beam, ε, from fiber is given by:

$$\varepsilon = \exp\left[-\frac{\left(x^2 + y^2\right)}{\omega_0^2}\right] \qquad \text{(Eqn. 3.2)}$$

ω_0 represents the beam waist of evenly distributed fundamental mode field distribution of circular beam input. Whereas the field distribution of waveguide field, E, is given by:

$$E = \exp\left[-\left(\frac{x^2}{\omega_x^2} + \frac{y^2}{\omega_y^2}\right)\right] \qquad \text{(Eqn. 3.3)}$$

Eqn. 3.3 says that the field distribution inside a waveguide is distributed at *1/e* in *x* and *y* directions of $2\omega_x$ and $2\omega_y$ respectively. Eqn. 3.1 can be reduced into a much simpler form which is shown in Eqn. 3.4:

$$\Gamma = \frac{\dfrac{2}{\omega_0}\left(\dfrac{1}{\omega_x\omega_y}\right)^{\frac{1}{2}}}{\left(\dfrac{1}{\omega_x^2} + \dfrac{1}{\omega_0^2}\right)^{\frac{1}{2}} + \left(\dfrac{1}{\omega_y^2} + \dfrac{1}{\omega_0^2}\right)^{\frac{1}{2}}} \qquad \text{(Eqn. 3.4)}$$

Eqn. 3.4 serves at the fundamental where waveguide is frees from any defects and possessed symmetric mode field. G. –r. Sui et al. [9] has showed the solution for waveguide which suffers from asymmetric mode field profile and maximum coupling efficiency, η_{max}, is given by Eqn. 3.5:

$$\eta_{\max} = \frac{4}{\left(\frac{W_{fo}}{W_{xo}} + \frac{W_{xo}}{W_{fo}}\right)\left(\frac{W_{fo}}{W_{yo}} + \frac{W_{yo}}{W_{fo}}\right)} \qquad \text{(Eqn. 3.5)}$$

W_{fo} is the beam waist of optical fiber; W_{xo} and W_{yo} is the beam waist of guided mode in x- and y- direction respectively [9].

Instead of using electromagnetism to define coupling efficiency, optical power of signals can also be used to elaborate the parameters. The formulation is still using the same field overlapping theory as the definition, but it is represented in a much simpler form compared to Eqn. 3.5 which is given by Eqn. 3.6:

$$\eta = \frac{P_E}{P_\varepsilon} \times 100\% \qquad \text{(Eqn. 3.6)}$$

where P_ε stands for the optical power from excitation and P_E is the transmitted optical power from waveguide field. This simpler elaboration is easier to implement as optical power can be easily measured using optical power meter solely. From Eqn. 3.6, the coupling loss (in dB) of aligned waveguide can be derived as follows:

$$\eta^* = \frac{P_E}{P_\varepsilon} \qquad \text{(Eqn. 3.7)}$$

$$\kappa = 1 - \eta^* \qquad \text{(Eqn. 3.8)}$$

$$loss, \alpha = 10\log_{10}(\kappa) \qquad \text{(Eqn. 3.9)}$$

$$\alpha = 10\log_{10}\left(\frac{P_\varepsilon - P_E}{P_\varepsilon}\right) \qquad \text{(Eqn. 3.10)}$$

with η^* and κ are the coupling ratio and loss ratio respectively.

3.2: Waveguides Alignment

There are two approaches used to perform waveguide alignment, active and passive alignment. Active alignment makes use of light coupling feedback loop to measure transmitted light at the output end of the under-test device in real-time to achieve desired coupling efficiency, whereas passive alignment is a method to place optical components into a single platform [1] where some may refer this as Silicon Optical Bench (SiOB) as silicon is the principle material for the platform [10-11]. Both of these methods have been developed for years for the sake of reducing the complexity of optical device alignment.Table 3.1 shows the advantages and disadvantages of both methods.

Table 3.1: Comparison between active and passive alignment.

Method	**Advantages**	**Disadvantages**
Active alignment	High degree of freedom, yields high quality alignment. Applicable to any optical devices. Active feedbacks to user.	Complicated alignment algorithm and calculations development. Requires high precision motorized controlled stages.
Passive alignment	Single platform for a complete optical module. Bridging with semiconductor technology.	Low coupling efficiency. Specific designed platform to suits different optical waveguides.

Introduction of active and passive alignment techniques is an alternative to the ideas of monolithic and hybrid integration of optical and electronic components where later integration techniques are still not well developed [12]. Monolithic integration is an idea to integrate both optical and electronics components on a single substrate in the front end fabrication process [4]. This integration technique has the advantages in data transmission and processing as it removes the needs to align every optical component individually. Hybrid integration is an integration technique to integrate different optical component to generate unique complex structure [4].Therefore, this method offers the advantage to produce customized optical chip with compact form. However, lensless coupling is the ultimate aim in this method, so the tendency to suffer from misalignment is considered high too [4, 12].

3.2.1: Active Alignment

As mentioned above, active alignment is an action where alignment activity is continuously being executed until the location of maximum output of signal is detected; it is therefore automated. This action can be done by developing a seeking and identify algorithm in conjunction with a high precision motor controlled stages system [5, 6, 9]. The algorithm can be designed in such a way to undertake the task automatically or with active feedback to users. In general, active alignment only works when 3 components are in place: algorithm, software, and hardware. This is pictorial via Fig. 3.3 below.

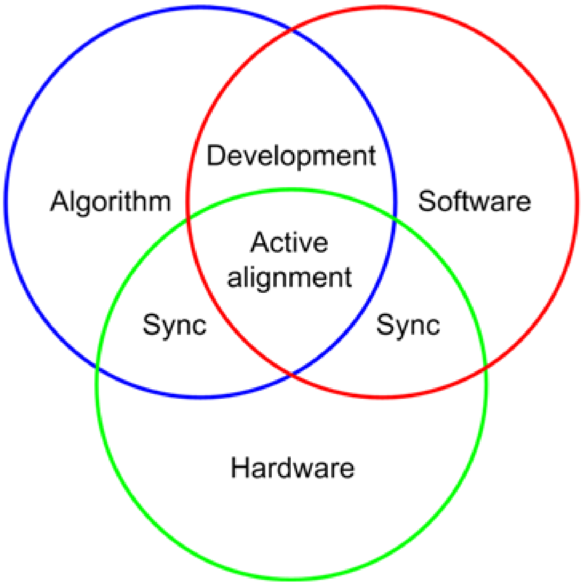

Fig. 3.3: Active alignment composition

In this case, alignment algorithm is defined as a set of rules or restrictions that define the tracing nature on position which corresponded to the maximum signal yield at the waveguide output. For smooth execution of an algorithm, it must consist of sequential instructions with details elaboration on dedicated task and communicating in proper programming language which can be understood by hardware. Since the primary goal of planar waveguide alignment is to pigtail the waveguide with fiber or fiber array with an input signal, it is therefore important to have pseudo codes or flow chart about the trend of the seeking procedure before program is designed. Pseudo code is an artificial and informal language that used to design algorithm [13]. For instance, as a component responsible for power comparison in a peak searching algorithm, the pseudo codes may appears as simple as below:

if p0 > p',

move stage to position corresponding to p0 and stop;

else continues with the comparison

Combined with proper planned flow chart, pseudo code of every single component of program is arranged accordingly and hence a complete alignment algorithm can be taken out from the picture. In fact, active alignment is a multidisciplinary research where it demands the development and optimization on multi-dimensional alignment algorithm, implementation on machine vision, and system design to improve alignment sensitivity [14, 15]. A more detailed look into algorithm development will be presented in Chapter 4 as the objective of this work.

Due to the structural property of planar waveguides, their performances are easily jeopardized by positional accuracy of light source. Automation at sub-micron regime offers the hand for the issue and is a perfect candidate for the old timer utilizing manual alignment operated under microscopes. Active alignment or automation able to deliver competence and consistent waveguide alignment throughput compared to manual alignment. Number of end product can be as well increased if automated waveguide alignment system equipped with packaging facility. If the alignment and packaging system works efficiently, assembly cost will then be further reduce too [7, 14].

3.3.2: Passive Alignment

Passive alignment, as depicted by the name, is a method to align fiber to waveguide passively by putting both of them on a custom made platform. This technique places the optical components in designated seat on platform without compromise the performance [16] and thus offers an advantage to assemble any optical module easily. Since a dedicated platform is required for this method, it is therefore reasonably important to well study the mechanical properties on the material used for platform fabrication. With proper techniques, passive alignment is able to yields high performance end-products to market. Surface Mount Photonics (SMP) is an example of passive alignment technique developed by D. W. Vernnoy et.al [16]. This technique is claimed to have the features such as performance-insensitive alignment for all optical waveguides, "global-top" encapsulation technique for hermetic packaging issue and is wafer level test and burn in ready [16]. Since this alignment technology is adapted to wafer level test and burn in techniques, production cost for an optical waveguide can be further reduced [16].

3.3: Device Coupling Techniques

Neither active nor passive alignment, coupling between any optical components is inevitable as it controls the percentage of input signal to be input to any devices. An appropriate selection on the coupling method ensures the planar waveguide functionality. Table 3.2 summarizes some commonly applied coupling method according to the setup.

Table 3.2: Commonly used coupling method

Method	Setup	Ref/s
Prism coupling	Light coupling via prism on top of waveguide	[17]
Free space coupling	Lens is used to collect and couple light into waveguide	[12]
Butt coupling	End-to-end coupling without any instrument	[12]

In this work, butt coupling has been chosen as the coupling method throughout the experiment according to the situation. Fiber which has the numerical aperture of about the same with single mode waveguide numerical aperture value is one of advantage of using butt coupling. Even though different in waveguide structure may greatly reduce the waveguide performance by inducing a percentage of loss, this situation still can be improved by having an optimized position of light source relative to the waveguide input [5]. Other reason for the choice of butt coupling method is that it requires no other extra apparatus hence eliminates the complexity of experiment and possibility of loss yielded by apparatus. This particular is important as we always wanted an aligned waveguide with high coupling efficiency.

3.4: Fundamental of Ultra Violet (UV) Laser Writing

Ultra violet (UV) laser writing onto optical planar waveguide is a relatively young technique to fabricate functional optical devices compared to the conventional, but it manages to steal the limelight once to be the subject for research and hence the implementation into waveguides fabrication due to its hassle free nature [18]. Deployment of this laser technology is not restricted in planar waveguides fabrication though, also in fabricating an optical device named after Sir William Bragg, Fiber Bragg Gratings (FBGs), which now showing remarkable applications in photonics instruments and modules. With determination, M. Svalgaard et. al [19] and D. Zauner et. al [20] have succeed in fabricating low loss planar waveguides; and now the highly functional optical devices for broadband add/drop multiplexing developed by C. K. Chow et. al [21] using this laser technology. Fig. 3.4 shows the illustration of direct UV writing.

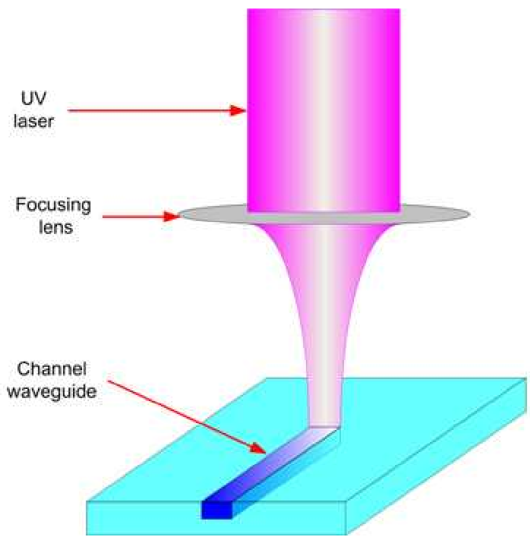

Fig. 3.4: Direct UV writing of channel waveguide

Origin of this technology is contributed by Chandross et. al in 1974 [22] in his work about the fabrication of optical waveguide in doped polymer film, and the phenomenon where refractive index changed due to UV irradiation at 364nm is named as "photo-locking". This "photo-locking" able to creates 'smooth interface and low optical losses which is hardly performed by the conventional process, according to them. Consecutive works on the phenomenon by Stewart et. al in 1979 has inspired the likelihood of having optically re-writeable planar waveguides [23]. A year before 1979, Bragg gratings were found to be self-constructed within a Germanium (Ge) doped optical fiber when an Argon (Ar) laser operating at UV-wavelength region was launched into it [24]. Formation of gratings structures was found to be closely associated with material behavior towards UV irradiation, where this special characteristic is known as photo-sensitivity and is similar with "photo-locking" phenomenon mentioned discovered later. Obviously, photo-sensitivity or photo-locking is the play maker of the game.

Apart from photo-sensitivity behavior of materials, the power received by the materials has decisive role on the strength of written channel waveguide. The power exposed name as *fluence* in the unit of $KJcm^{-2}$ is an approximation expression and is defined by Eqn. 3.11 [19, 25]:

$$F = \frac{I \bullet a}{v} \qquad \text{(Eqn. 3.11)}$$

where I is the averaging power density of writing spot in the unit of $KWcm^{-2}$, a is the diameter of the writing spot in μm and v is the translational speed of stage holding specimen in the unit of μms^{-1}. This parameter is taking into consideration when designing an optical circuitry which depends on the speed of the translational stage. For simplicity, when direct UV writing a simple X-coupler, the refractive index change at the intersection of both channel waveguides must be indifferent from the index change in elsewhere of channel waveguide; hence the speed of translational stage when reaching that particular point must be adjusted if the writing process is started channel by channel to ensure total *fluence* received at that point is the same with elsewhere.

3.5: Photosensitivity

Observation of the photo-sensitivity characteristic by most glasses is associated with the glass matrix modification when they are interacting with photons originated from UV region; or, it can be said that the quasi-permanent change of material's refractive index when exposed to UV [25]. Change of refractive index depends on several parameters such as material composition, thermal history of material, wavelength and power density of light used for exposure as well as the polarization of light [25, 26]. Since photo-induced refractive index changed is a quasi-permanent process, hence, the effect can be reversed easily through over-exposure of the UV light and thermal annealing process [25, 27].

Color center model, densification-compaction model [28-29] and dipole-quadrupole model [26, 27, 29] are the available models to understand the exhibition of photosensitive macroscopically, or microscopically. Macroscopic says the macroscopic effects like compression contribute to the change of refractive index; whereas the index change caused by defects formed in glass matrix is reviewed from microscopic aspect [25, 26]. Refractive index change from microscopic can be studied through *Kramers-Kronig relation* given in Eqn. 3.12 [25, 27-28].

$$\Delta n(\lambda) = \frac{1}{2\pi^2}\int_0^\infty \frac{\Delta\alpha(\lambda')d\lambda'}{1-(\lambda'/\lambda)^2} \qquad \text{(Eqn. 3.12)}$$

$\Delta n(\lambda)$ and $\Delta\alpha(\lambda)$ are the changes of material's refractive index and absorption coefficient with respect to wavelength.

3.6: Summary

A brief discussion on the theory of alignment and the type of alignment has been presented in this chapter. It is clearly seen that the waveguide alignment can be defined in two different manners, theoretical and practical. Both of these definitions find their own value in different application or condition. For instance, theoretical definition is useful when analyzing the field distribution from waveguide when it is coupled with an incoming field at certain orientation from normal.

Selection of alignment method is an important aspect needed take into considerations when comes to packaging. Both active and passive alignment methods offers different advantages as well as the disadvantages, hence, consideration such as the flexibility of method, balance between cost, time and equipments involved has to review in details before the decision being made.

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