A Dissertation Report on

Interfacing Components for Photonic Integrated Circuits

Submitted in the partial fulfilment of the requirements for the degree of Master of Technology in Solid State Electronic Materials

By

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Declaration

I hereby declare that the project entitled "**Components of Photonic Integrated Circuit**" submitted by me to the Department of Physics, IIT Roorkee in partial fulfilment of the requirement for the award of the degree of Master of Technology in Solid State Electronic Materials is a record of my own work carried out during the period July 2017 to May 2018 under the supervision of Dr. Rajesh Kumar.

Place: Roorkee (SHIVANI SINGH)
Date: M.Tech. SSEM
I.I.T. Roorkee

Certification

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Place: Roorkee (Dr. Rajesh Kumar)
Date: Department of Physics
I.I.T. Roorkee

Acknowledgement

It is a matter of great pleasure to express my gratitude to Dr. Rajesh Kumar for his valuable supervision, convincing discussions, constant motivation throughout this work and for his valuable time.

I would like to thank all the Faculty Members and the Head of the Department, Dr. K.L.Yadav of the Department of Physics for their support and guidance.

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I would also like to express my gratitude and respect to my family and friends.

Abstract

This thesis reports the results of parametric variations of various components of *photonic integrated circuit* consisting of an Optical Fibre, Linear Diffraction Grating, Straight Taper and Single Mode Waveguide. The structure for the Linear Grating was designed and simulated at different grating periods and grating depth. The Straight Taper Waveguide was designed and simulated for different taper lengths and smooth and sectional taper designs. The combination of Optical Fibre and Linear Grating was simulated at parametric variation of gap between the two. Moreover, various combinations of all these components were designed and simulated. Finally, the entire setup of all the components was designed and simulated.

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Chapter 1: Introduction

Photonics is the study and application of light. At the core of photonics are the technologies for generating, transmitting, modulating, amplifying and detecting light, and especially utilizing it for practical purposes. Thus, it builds heavily on optical technology, in association with the modern developments such as lasers, LEDs, amplifiers etc.

Common applications include:

- ***Information Technology***: for e.g. optical fibre communications, optical data storage, free space optical communications and may be in future also in optical computing.
- ***Sensing***: for e.g. fibre-optic sensors, industrial process control, infrared motion detectors and high-speed cameras.
- ***Manufacturing***: for e.g. laser material processing, printing, semiconductor (SC) chip manufacturing.
- ***Lighting***: for e.g. energy efficient LED (light emitting diode) illumination.
- ***Health Care***: for e.g. medical diagnostics and therapy in the field of ophthalmology and cancer-research, biotechnology etc.
- ***Defence and Space Technology***: for e.g. satellite surveillance systems, navigation, imagers, missile guidance, and high-power directed-energy weapons.

Analogy with electronics: In the same way electronics utilizes electrons, photonics uses photons.

Features	**PIC**	**EIC**
Data Carrier	Photons	Electrons
Type of Components	Functional Optical Devices	Transistors
Number of Components Integrated	Limited to few hundred	Range into millions
Substrate	Many different materials in a single chip	Fits nicely onto Silicon

Table 1: Comparison between PIC and EIC

Importance of Photonics

Photonics is one of the key technologies of the 21st century. In the form of optoelectronics, it supplements electronics and reflects strong market growth that is expected to rise in the coming years. So far, it has been able to achieve deep penetration in mass markets, such as laser diodes in DVD/ CD players and other data storage equipment. Immense growth opportunities may arise from development of Si photonics and related technologies of photonic integrated circuits (PICs), from LEDs with improvised efficiency and output power, and from laser types (eg. VECSELs) suitable directly for cost-effective mass production.

Silicon Photonics

An immensely powerful technological platform, for applications in the field of microelectronics based on Si chips has been under development in recent past. It, now forms basis for large memory circuits, complex microprocessors, and several other analog and digital electronics. With the introduction of the SOI (silicon on insulator) technology, it's been demonstrated that the photonic functions can be effectively integrated into such technological platform, so that Si based *PICs* became reality.

In this field, different types of optical components may be connected to each other through Si waveguides. These circuits may be used for establishing very fast communication between different circuit boards, between the chips on same board, and also within single chips, for e.g. connecting the different cores of the microprocessor. This technology can also be useful in other areas of optical communication, such as (FTTH) fibre to the home.

Technological Challenges

Although the possible merits of silicon-based photonics are huge, there are also very substantial challenges for such a technology:

- Due to an indirect bandgap, silicon is a very inefficient light emitter. Although various tricks have been developed to get around this, the laser or amplifier performance of silicon-based devices cannot compete with that for other approaches, based on, e.g., gallium arsenide or indium phosphide.
- The bandgap of silicon is larger than the desirable value, thus making it nearly impossible for detecting light in telecommunication spectral range of around 1310 and 1550 nm.

- Silicon has no $\chi^{(2)}$ nonlinearity, making it impossible to realize electro-optic modulators with this material.
- The heat emanated by the laser source on the chip may also be more than that is convenient.
- Optical connections often do require a precise alignment, that demands improvised alignment technologies for more efficient mass production.

State of Research

- For **guiding light in WG**, silicon is considered suitable. There are rib WGs with oxide cladding, exhibit propagation losses of quite below 0.1 dB/mm. The transparency range of Si ranges from ≈ 1100 nm to the far infrared region. This tight mode confinement permits sharp bends without any excessive bend loss. Also, it enables the utilization of non-linearities for certain key functions, for e.g. amplification via four wave mixing.
- For **amplifiers and laser light sources**, the indirect band-gap of Si is rarely usable. Considerable progress has been attained using porous Si and its nanoparticles in SiO_2. However, the performance achieved in this case cannot compete with the performance of Indium Phosphide based devices. But Si permits efficient Raman amplification, as the Raman-gain-coefficient for silicon is extremely high and the WGs bound the mode into a very small region.
- **Si based optical-modulators** may be realized using Mach Zehnder interferometers (MZIs) and phase modulation through change in carrier-density. Injecting carriers using an electrode will change the refractive index of 1 arm of interferometer, which will translate the phase change in turn into the change in the power transmission. Yet another possibility can be using a microring resonator. Transmission bandwidths of multiple gbps may be achieved through such devices.
- **Si photo-detector** is usually sensitive only for spectral wavelengths below 1100 nm. Photodetectors for telecom wavelengths around 1550 or 1310 nm are possible using alloys of SiGe. Problems may arise due to resulting lattice mismatch that might lead to crystal defects.

Chapter 2: Theory

2.1 Optical Fibre

Optical fibres form the core components in the field of fibre optics. They can be potentially as long as hundreds of kilometres, and are, in contrast with other WGs, also fairly flexible.

The commonly used glass is made of silica, either in pure form or with some dopants. Silica is so widely used owing to its outstanding properties, extraordinarily high mechanical strength against tensile and compressive bending and particularly its potential for the extremely low losses during propagation. Nevertheless, for certain special applications, specialty fibres that are made from some other types of glasses, for example fluoride fibres.

Most of the optical fibres that are used in the laser technological field tend to have a core that has refractive index somewhat higher than the refractive index of surrounding medium (*cladding*). The simplest of the cases is that of a *step index fibre*, where the refractive index is kept constant within the core and also within the cladding. Thus, the index-contrast between the core and the cladding determines numerical aperture (NA) of fibre and is normally small, such that the optical fibres are weakly guiding the light. Light, thus, launched into the fibre is guided through the core, that is, it mainly propagates within core region, though the distribution of intensity might extend a little beyond the core also. Because of the guidance of light and low propagation losses during propagation, the optical intensity may be maintained over very long lengths of the fibre.

2.1.1 Applications of Optical Fibres:

Some of the most important applications of optical fibre include:

- Optical fibre-communications employ the optical fibres usually for long range data transmission, but sometimes for short distances also. Immense amounts of data may be quickly sent via a single fibre that is also immune to external influences like electric field and magnetic field and thus highly secure.
- Active fibre optic devices may contain some rare earth doped fibres. The fibre lasers may generate the laser light at varied wavelengths and fibre amplifiers may be used for enhancing the optical power or for amplifying the weak signals.

- Fibre optic sensors may be used for strain measurements and distributed temperature in oil pipelines, buildings and the wings of airplanes.
- Passive optical-fibres are useful to transport light from the source to another point; for eg purpose of illumination, power over fibre and diode pumping of lasers. Thus, they behave similar to electrical wires in electronic devices.

Thus, fibre-optics has now, become a significantly important area in the technology of photonics.

2.1.2 Fibre Modes: Single-mode versus Multimode Fibres

An optical fibre may support one or many *guided modes*, the intensity distributions for which are located at/immediately around the core of the fibre, although part of the intensity might propagate within fibre cladding also. The optical power inside the cladding modes, usually gets lost after some distance of propagation, however, in some cases, may propagate over much longer distances. Beyond region of cladding, there normally is a polymer coating that acts as a protective layer, that gives the fibre much more mechanical strength, better guard against moisture, and it also helps in determining losses for the cladding modes. Such type of buffer-coatings might consist of silicone, acrylate or polyimide. Further, at the ends of the fibre, the coating has to be, often, stripped off.

An important distinction is that between single-mode and multimode fibres:

Single Mode	**Multimode**
Small core (8-10um)	Larger core than single cable (50-100um)
Less dispersion	Greater dispersion and therefore, loss of signal
Employed for long distance applications (100 kms)	Used for shorter distance application, but shorter than single-mode (upto 2 kms)
Carries a single ray of light, usually generated from a laser with a narrow spectral width	Uses Led source that generates different angles along cable
Higher transmission rate without signal distortion	Signal distortion at the receiving end, with unclear and incomplete data transmission.

Table 2: Single mode vs Multimode

- Single mode fibres normally have relatively smaller core with a diameter of a few micrometres and may guide a single spatial mode only that has roughly a Gaussian-shape. Efficient launch of light into a single mode fibre normally requires laser source with precise alignment of the focusing optics and good beam quality for achieving mode matching. In case of multimode fibres, the alignment tolerances are much lower in terms of the position but higher in terms of the angle.
- In multimode fibres there are relatively large core radii or/and large refractive index difference in between cladding region and core region, that aids them to support multiple modes having varied intensity distribution. In this particular case, spatial profile of the light that exits at the end of the core region will depend on the conditions of launch, which will determine the distribution of power in various spatial modes.

Long range optical fibre communication systems normally use single mode fibres, due to different group velocities for different modes will distort the transmitted signal at the high data rates known as intermodal dispersion. However, for relatively shorter distances, the multimode fibres are much more convenient as in this case, demands on the light sources and alignment of components are lower. Thus, local area networks (i.e., LANs), except the ones for the highest bandwidth, usually employ multimode fibre.

Single mode fibres are usually used for amplifiers and fibre lasers. Multimode fibres, therefore, are often used for transport of the light from the laser source to a place where it is required, particularly where light source has relatively poor beam quality and (/or) high optical power requiring a larger mode area.

2.1.3 Main Parameters:

The specifications for fibre may be characterized by 2 parameters only, the radius of the core region, *a* and the difference between refractive indices Δn of core region and the cladding region. General values of core radii lie in the range of a few micrometres in case of single mode fibres and tens of micrometres or greater in case of multimode fibres.

In place of difference of refractive indices, the numerical aperture may be used, which can be defined as

$$\mathrm{NA} = \frac{1}{n_0}\sqrt{n_{\mathrm{core}}^{2} - n_{\mathrm{cladding}}^{2}}$$

Which is the sine value of maximum acceptable angle by the incident ray calculated with respect to fibre axis. The N.A. also helps in quantifying guidance strength. The sensitivity to bend losses strongly reduces with increase in numerical aperture, which helps in strong confinement of the field mode in the core.

The *V* number is also used along with NA, and is given as below

$$V = \frac{2\pi}{\lambda} a \,\mathrm{NA} = \frac{2\pi}{\lambda} a \sqrt{{n_{\mathrm{core}}}^2 - {n_{\mathrm{cladding}}}^2}$$

It is just like normalized frequency. Condition for single mode confinement is given as *V* number is less than 2.4005. Multimode fibres may have large *V* values.

2.1.4 Optical Fibres Vs Electric Cables

In some technical quantifiers, such as data transmission in optical domain over long distances or even in between computer chips and or optical fibres compete with electric cables. When compared with the electric cables, they have many advantages:

- The capacity of a fibre for optical data transmission is orders of magnitude higher than for any electric cable.
- Transmission loss of a fibre is very low: quite below 0.001 dB/m for the optimum wavelengths, which is 1.55 μm.
- Large number of channels may be amplified again in a single fibre amplifier, when required for very large distance of transmission.
- Optical data connections through fibres are comparatively difficult to tap and change, which provides additional security even without using encryption techniques. Optical fibres can be employed for very high security, quantum cryptography.
- Fibre cables are immune to EM interferences, problems with ground loops and thus are highly secure.
- There is no risk of fire hazards or that of triggering any explosive substances (except when carrying any high optical power break).

On the other hand, fibres also have certain disadvantages:

- Fibre connections are relatively sensitive and a bit difficult in handling, especially when single mode fibres are in application. High cleanliness and precise alignment are essential. For these reasons, fibre connections are competitive only if high transmission bandwidth may be utilized.
- Glass fibres mustn't be bent very tightly, as this is likely to result in higher bending losses and even breakage. This might be a problem in cases like fibre to the home technologies.

If attenuation is insignificant (a=1), critical coupling takes place at symmetric coupling. For lossy resonators, critical coupling takes place when the losses equalize with the coupling.

2.2 Silicon Waveguide

An optical WG is inhomogeneous structure to guide light that is to restrict the spatial region where light propagates. Generally, WG contains a region of increased refractive index of core, compared with the surrounding medium of *cladding*.
We can see WGs exhibiting 2D guidance, thus curtailing the extension of guided light in 2D and allowing the propagation exclusively in one dimension. The most elementary type of 2D WG is optical fibre. One-dimensional waveguides are also there, often known as planar waveguides.

2.2.1 Waveguide Modes

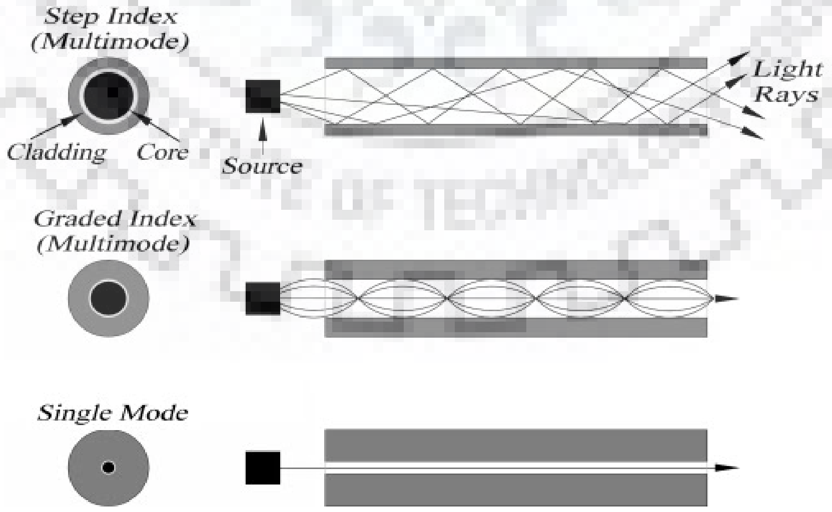


Figure 1: Waveguide modes

For WG having large extensions, ray optics are sometimes used for explaining the propagation of light injected. However, it may become invalid when effect of interferences occur, and this is particularly the case for small waveguide dimensions. In such case, description of the wave of light is needed normally on the basis of Maxwell's equations.

It is mundane to consider the distribution of field for a polarization in a plane perpendicular to the propagation direction and given optical frequency. Those which don’t change during propagation, apart from common phase change. Association of so called WG modes are with such field distributions. Each mode has a certain fixed propagation constant, the imaginary part of that propagation constant numerically quantifies the phase delay per unit propagation length. A fibre has a large number of unguided modes know as *cladding modes*, which aren’t restricted to only vicinity of the fibre core.

2.2.2 Applications:

- Optical cables help in transmission of light over long distances, without heavy losses.
- On *PIC*, as used in *Si photonics*, WGs guide light among different optical components.
- In future, Si WG will find a place on polymer waveguides in circuit boards of digital processor chips can be used to enhance optical data transmission speed among components of computers.
- WG is used for stripping off the higher order transverse modes, thus acting as a *mode cleaner*.
- In some cases, an interaction of the guided light with the material is used, e.g. in certain *waveguide sensors*.
- WGs may also be employed light beam splitters and combiner.

2.3 Diffraction Gratings

It is an optical device that exploits the phenomenon of diffraction. It consists of a periodic structure, which results in spatial variation of optical amplitude and/or phase. *Reflection gratings,* are the most common, with a reflecting surface of periodic surface relief resulting in phase changes that are position-dependent. Also, there are *transmission gratings*, wherein transmitted light undergoes phase changes that are position-dependent, caused by surface relief.

2.3.1 Details of Diffraction at a Grating

Incident beam which has angle θ with the normal has wave vector component along the plane of the grating which is equal to $k * \sin\theta$, where $k = 2\pi / \lambda$ where λ is the wavelength. Ordinary reflection leads a reflected beam with vector component in plane wave equal to $-k\,.*\sin\theta$. Due to the phase modulation at grating, there may be more components reflected with the wave vector components in plane equal to $-k\,.*\sin\theta \pm 2\pi.\,/d$. These components corresponding to orders of diffraction in the range of -1 to 1. Thus, the corresponding output beam angle against the normal direction is derived:

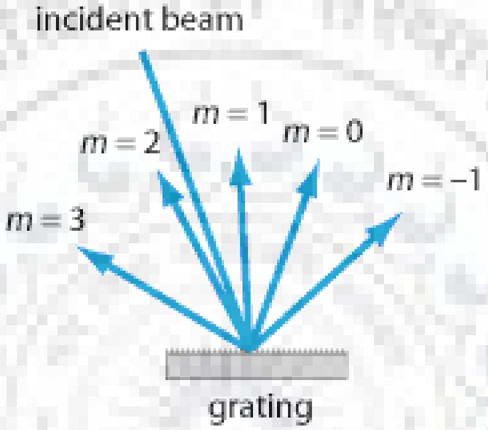


Figure 2: The Output beams for all diffraction orders possible at a grating.

$$\sin\theta_{out} = -\sin\theta_{in} \pm \frac{\lambda}{d}$$

If the phase effect of grating does not have a sinusoidal shape, it may undergo multiple diffraction orders *m*, and from following equation, output angles might be calculated:

$$\sin\theta_{out} = -\sin\theta_{in} + m\frac{\lambda}{d}$$

Sign conventions can be used for different diffraction orders. If the above equations lead to value of sin θ_{out} greater than 1; then, diffraction order for that doesn't exist.

2.3.2 Distribution of the Output Power on the Diffraction Orders

The distribution of output power over different diffraction orders is an important aspect i.e., the *diffraction efficiency* for different diffraction orders. This will depend on shape of phase changes that are wavelength-dependent. Generally, the diffraction efficiencies might be calculated using diffraction theory.

Diffraction gratings can be optimized in such a way so that the most power gets directed in certain diffraction order, resulting in higher diffraction efficiency of the particular order. Such optimizations will lead to *blazed gratings*, where phase change (position-dependent) is described by a function shaped like a. Slope of corresponding profile of surface should be optimised as per given conditions within terms of the wavelength and input angle.

2.3.3 Specifications for Diffraction Gratings

The importance of diffraction gratings is also due to the fact that they reflect or transmit light at only discrete angles and angles of diffraction orders are sensitive highly to wavelength of incident light. There are two important specifications of a diffraction grating. First is direction of diffracted beams i.e., set of angles by which incident light is diffracted for certain wavelength and incidence angle. It depends on material parameters of transmitted and incident media and period of diffraction grating only, and solved using simple geometric relation. Second is the efficiency i.e., ratio of powers in each diffractive order relative and total power incident. This will depend strongly on structure and physical shape of the grating and is tougher to solve.

2.3.4 Types of Diffraction Gratings

Broadly, diffraction gratings can be divided into 2 categories: Amplitude gratings and Phase gratings.

1. Amplitude gratings

These are a simple array of multiple slits, that are formed either by etching out an opaque surface, or combining fine wires in a grid manner. These modulate only the amplitude spatially of transmitted wave by means of periodically blocking the beam, or by attenuating it very slightly.

2. **Phase grating**

These consist of an array of very narrow ridges that alternatively repeat indices of refraction. These modulate spatially only phase of transmitted wave by means of periodically altering phase of parts of the beam which transmit through the ridges that have refractive index alternating. The 2 important categories of these gratings: surface relief grating and volume grating.

(i) **Surface Relief Gratings**

In these, there exist periodic changes in physical topography of the grating. The 2 indices of refraction alternating are that of substrate of grating and of cover medium, which is usually air:

1. **Binary Grating**
   The most common example of surface relief grating consists of periodic thin rectangle shaped ridges. This type of grating is referred to as a binary grating. It is important because it can be easily manufactured by the method of photolithography. Anyhow, it is a bit difficult to manufacture binary gratings which has small periods.
2. **Sinusoidal Grating**
   The sinusoidal grating is important as it can be easily fabricated by holographic recording or recording the sinusoidal interference between the 2 uniform beams.
3. **Blazed Grating**
   The blazed grating too is an important type of grating as it exhibits strong preferential coupling into one of its several diffractive orders. It is recommended in cases wherever efficiency is a critical parameter such as optical interconnects.

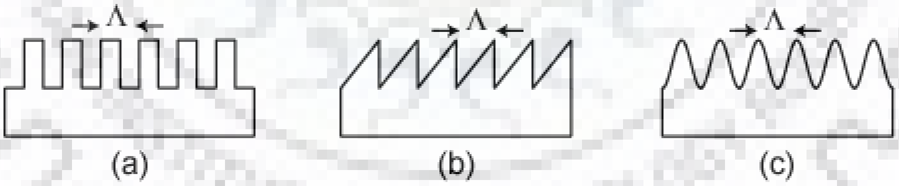


Figure 3: Examples of surface relief gratings: (a) binary, (b) blazed, (c) sinusoidal

(ii) **Volume Gratings**

A volume grating has a flat surface topography. The periodicity of the grating results from the alternating index of refraction in between the repeating periodic sections. One important advantage of volume gratings is that direction of periodicity can be easily made in direction other than that parallel to substrate surface. By the virtue of this property, volume gratings can be made with efficiencies of almost as 100% into a desired diffractive order.

2.3.5 Applications of Diffraction Gratings

Diffraction gratings have many applications. In the following, some prominent examples are given:

- They are used in *grating*s pectrometers, where the wavelength-dependent diffraction angles are exploited.

- Pairs of diffraction gratings can also be used as dispersive elements without wavelength dependent angular changes of the output. Such grating components can be used as compressors and dispersive pulse stretchers, such as in context of the chirped pulse amplification.

- Diffraction gratings are also used for wavelength tuning of lasers.

- In spectral beam combining, one often uses a diffraction grating to combine radiation from various emitters at slightly different wavelengths into a single beam.

2.4 Photonic Integrated Circuit

Photonic integrated circuits consist of the devices on which some or even many optical (sometimes electronic) components are incorporated. The technology of these devices is known as ***integrated-optics***. PICs are generally manufactured using wafer scale technology (including lithographic fabrication) on substrates (known as chips) of silica, silicon, or a non-linear crystal material such as lithium-niobate ($LiNbO_3$).

The substrate material already determines a number of features and limitations of the technology:

- ***Silica on silicon integrated optics*** uses silicon wafers, for which many features of the powerful micro-electronics technology may be used. SiO_2 WGs allow the realization of filters, couplers, power combiners and splitters, and even active elements with optical gain. They can also be connected to optical fibres.

- An area of strong current interest is ***silicon photonics***, where photonic functions are implemented directly on silicon chips.

- A photonic integrated circuits technology that has been already commercialized is based on ***Indium-phosphide*** (InP); and is mainly employed in the field of optical-fibre communications.

- WGs can be fabricated on ***SiO_2 glass*** (i.e., fused silica) for eg. with the lithographic techniques consisting of chemical processing or in-diffusion of dopants, or those with laser micro-machining.
- ***Lithium-niobate*** ($LiNbO_3$) is also suitable for the devices performing non-linear functions, for eg. electro-optic modulators or acousto-optic transducers.

Photonic integrated circuits may host either large arrays of identical components, or may contain complex circuit configurations. However, for various reasons the complexity achievable is not nearly as high as for electronic integrated circuits. One of the principle applications of PICs is employed in the field of optical-fibre communications especially in the case of fibre-optic networks, though they may be used for, e.g., optical sensors and in the field of metrology also.

Chapter 3: Computer Simulation Software

CST Studio Suite is a powerful simulation platform for all kinds of electromagnetic field problems and related applications. The program provides a user- friendly interface to handle multiple projects and views at the same time, each of which may belong to a different module.

One of the outstanding features of the environment is the seamless integration of various simulation methods and strong interoperability management.

The CST STUDIO SUITE software package provides the following simulation modules:

- CST MICROWAVE STUDIO
- CST EM STUDIO
- CST PARTICLE STUDIO
- CST DESIGN STUDIO^{TM}
- CST PCB STUDIO
- CST CABLE STUDIO
- CST MPHYSICSSTUDIO

3.1 Structure Modelling

CST MICROWAVE STUDIO, CST EM STUDIO, CST PARTICLE STUDIO, and CST MPHYSICS STUDIO share a common structure modelling tool.

In order to simplify the definition of frequently used materials, a material database is available. Before a material definition from the database can be used, one has to add it to the current project.

One can change the component assignment of a shape by selecting the shape and choosing *Component.*

The component assignment of a shape has nothing to do with its physical material properties. In addition to its association with a particular component, each shape is assigned a material that also defines the colour for the shape's visualization. In other words, the material properties (and colours) do not belong to the shapes directly but to the corresponding material. This means that all shapes made of a particular material are drawn in the same colour.

3.2 Post-processing

Once a simulation is completed, result data will typically be shown in the navigation tree. CST STUDIO SUITE contains powerful post-processing capabilities which include various options for visualizing the results and calculating secondary quantities.

In order to reduce the effort required for obtaining typical parametric results, all zero and one dimensional data points / result curves are stored parametrically by default.

Once a computation has finished, selecting a result from the navigation tree will display the corresponding result curves for the current parameter values.

3.2.1 Post-processing Templates

The *Post-processing Templates* allow for flexible processing of 2D/3D Fields, 1D Signals, or scalar values (0D Results).

All defined *Post-processing Templates* are evaluated after every calculation during parametric sweeps and optimizations. The calculated data is then stored parametrically to allow for flexible access to the entire data set.

The template based post-processing results are managed as follows:

- 1D results are shown in the navigation tree under *Tables□1D Results□*...
- 0D results are shown in the navigation tree under *Tables□0D Results□*…Additionally, the latest result value is shown in the *Value* column of the task list.
- Templates with a “-“ sign in front of their name do not add useful results to the navigation tree’s *Tables* folder, but store their results at other locations. Please refer to the corresponding template’s description for more information.

3.3 Result Navigator Window:

The result window offers a processed data plots to visualise the quantity of showed results and wanted parameter ranges or plot where 0D comes about. Changing the choice in the route tree enables you to review different outcomes process of the dynamic parameter mix determination.

The parametric plotting aid allows for easy access of particular parametric results without need for further complex steps of more advanced post-processing operations. The automatically recorded parametric results can be used directly for optimization.

The solvers enlisted in CST EMC STUDIO are selected to allow a wide range of E.M.C. workflows to be carried out in straight forward fashion.

- The TLM (transmission line matrix) solver is time domain method which especially is well suited to E.M.C. simulations. The TLM solver may use octree gridding to reduce simulation time on extremely complex structures, and supports analytical compact model representation of fine detail.
- Transient solver, which is an application of the Finite Integration technique (FIT), it is general purpose time domain solver (TDS) and is used for performing broadband simulations related to radiated emissions.
- The frequency domain solver is based on the finite element method (FEM), and is often used to simulate conducted emission. The frequency domain solver includes a special meshing engine specially optimized for Printed circuit boards, which allows complex boards for faster simulation than conventional methods.
- Cable harness solver is specialized solver for simulating cables in complex environments. There is bidirectional coupling between cable harness solver and time domain solver, allowing cable harness for integration in a 3D model and analyzed using bidirectional simulation.

CST microwave studio (CST MWS) is a specialized tool for the 3D Electro-Magnetic simulation of high frequency components. CST MWS' unparalleled performance making it the first choice in the leading R&D departments.

C.S.T M.W.S. empowers us to perform a faster and more accurate analysis of high frequency (H.F.) simulating structures such as filter, planar and multilayer structures, antenna, coupler, and S.I. and

E.M.C. effects. Exceptionally user friendly, C.S.T M.W.S. quickly gives you an insight into the E.M. behavior of your high frequency designs.

C.S.T. promotes Complete Technology for 3D E.M. Software users are given great deal of flexibility in tackling a wide range of application through a variety of options available in solver technology. Besides this, the broadly applicable Time Domain and the Frequency Domain solver, C.S.T. M.W.S. offers further solver modules for specific applications. Filters for importing specific C.A.D. files and also extraction of S.P.I.C.E. parameters enhance design possibilities and save time. In addition, C.S.T. M.W.S. can be utilized in various industry standard workflows through the CST.

3.4 Post-processing Formats: -

The post-processing Formats take into account adaptable handling of 2D/3D Fields, 1D Signs, or scalar qualities. All characterized post processing Layouts are assessed after each count amid parametric scopes and enhancements. The ascertained information is then put away parametrically to take into account adaptable access to the whole informational collection.

CST promotes Complete Technology for 3D EM. Users of our software are given great flexibility in tackling a wide application range through the variety of available solver technologies. Besides the flagship module, the broadly applicable Time Domain solver and the Frequency Domain solver, CST MWS offers further solver modules for specific applications. Filters for the import of specific CAD files and the extraction of SPICE parameters enhance design possibilities and save time. In addition, CST MWS can be embedded in various industry standard workflows through the CST STUDIO SUITE® user interface.

Chapter 4: Simulations and Results

Results under this section are for structural dimensions

4.1 Single Mode Waveguide

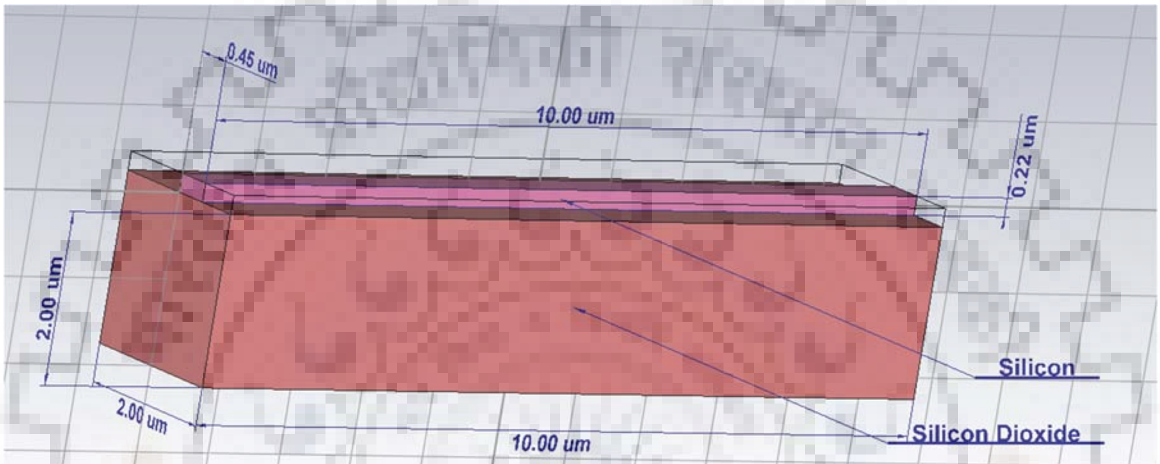


Figure 4(a): Single Mode Waveguide

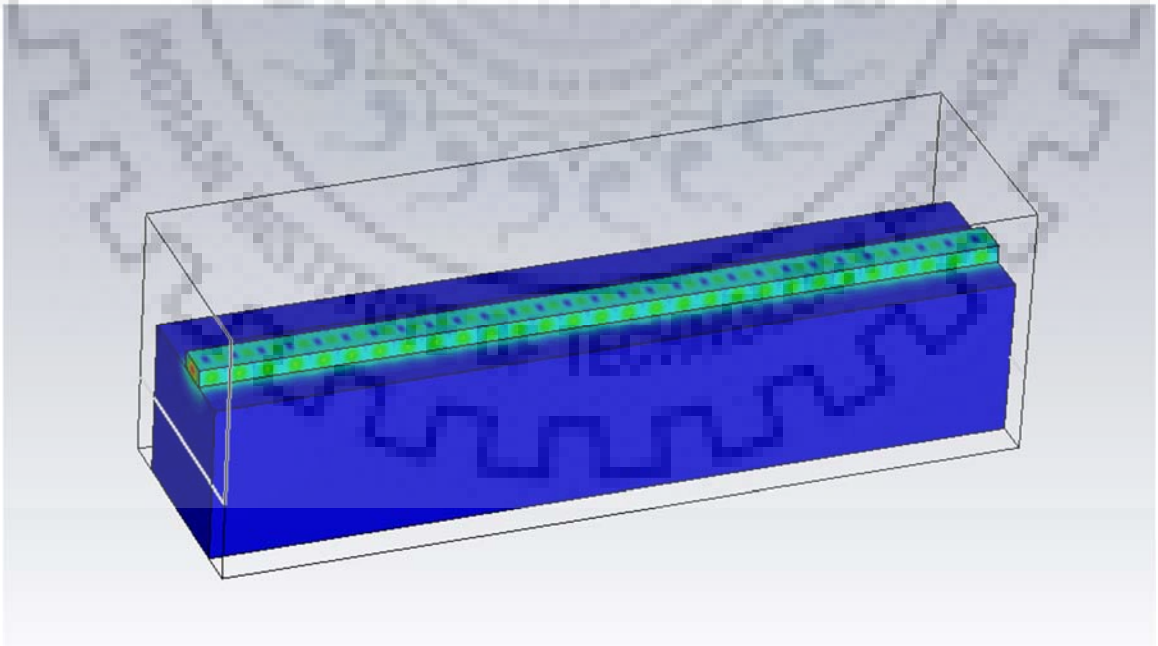
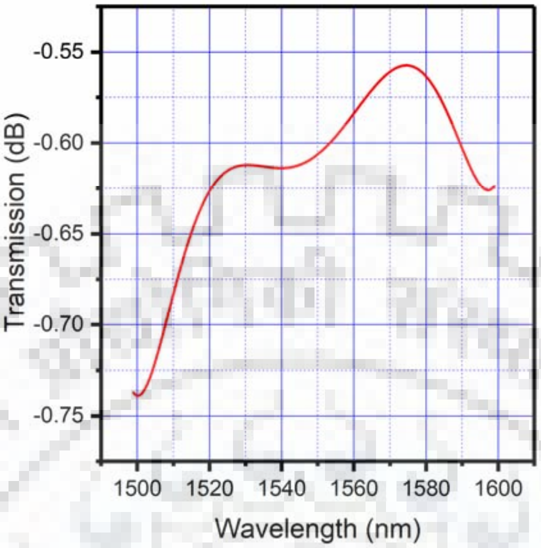


Figure 4(b): Simulation Structure of Single Mode Waveguide



Interpretation

The simulation and graph for a single mode waveguide shows that with increase in the wavelength of incident light, transmission through the waveguide first increases and then decreases. The maximum transmission is observed in the range of 1550nm-1570nm.

4.2 Linear Grating

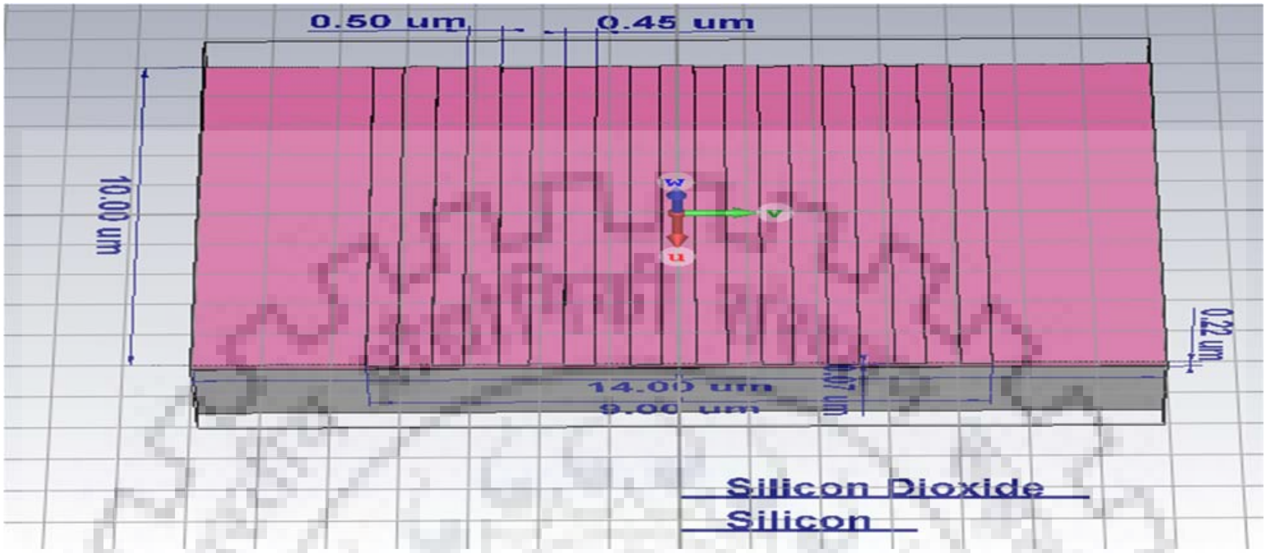


Figure 5(a): Linear Grating

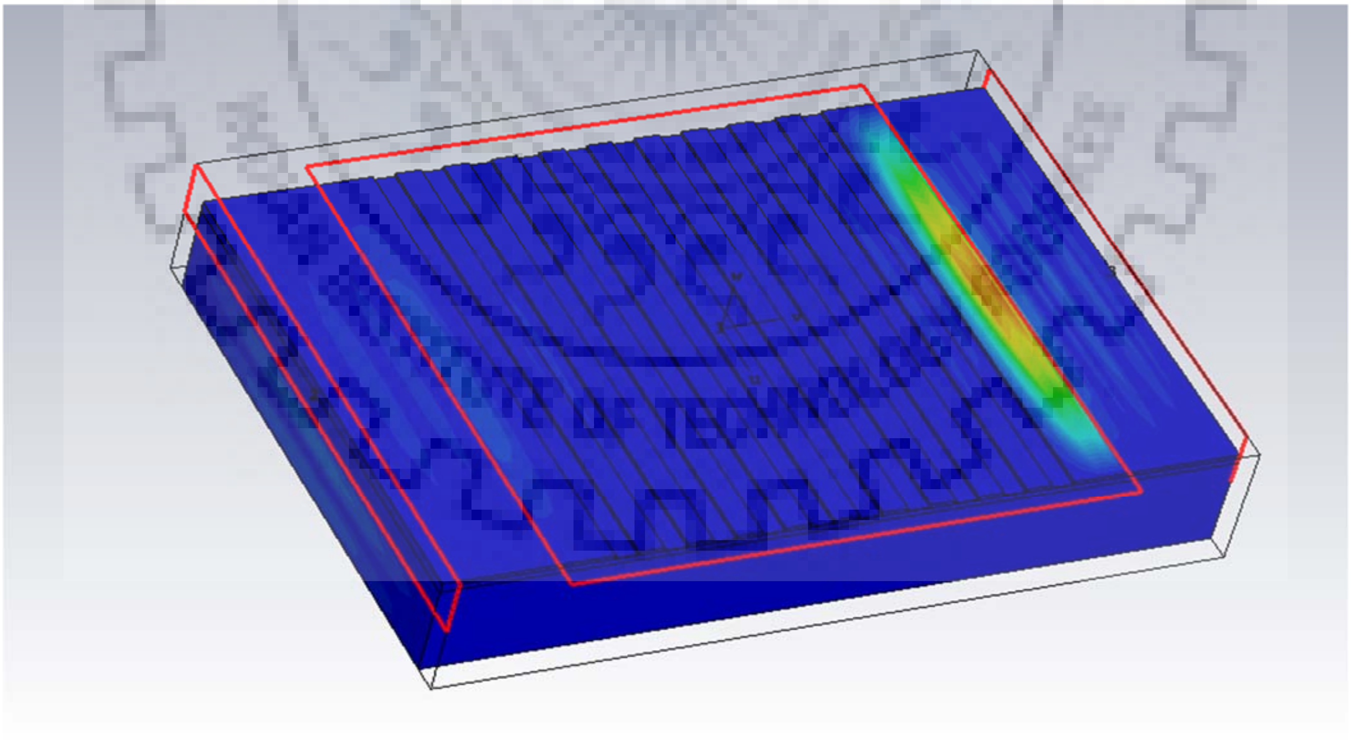
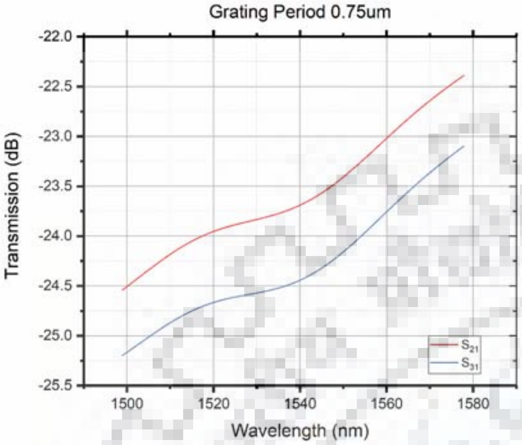
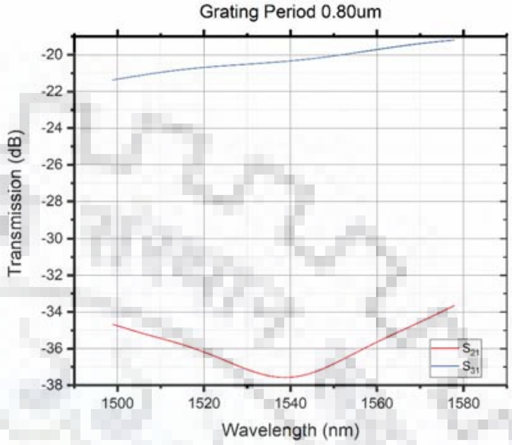


Figure 5(b): Simulation Structure of Linear Grating

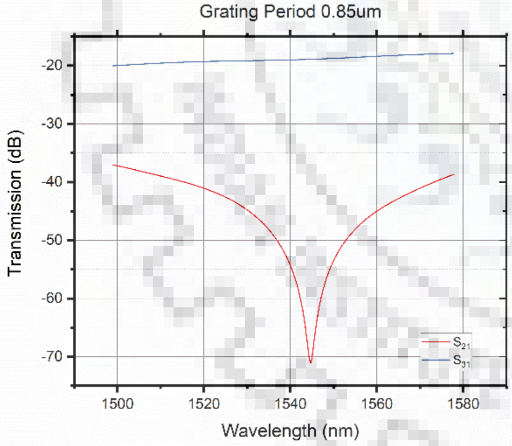
4.2.1 Grating Period Variation



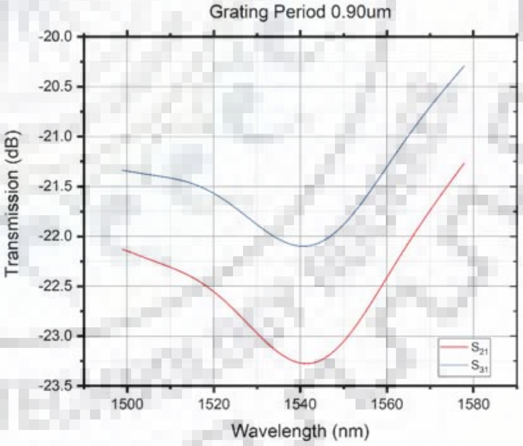
Grating Period 0.75um



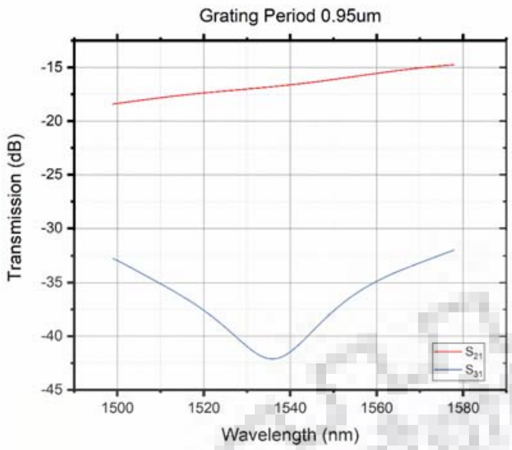
Grating Period 0.80um

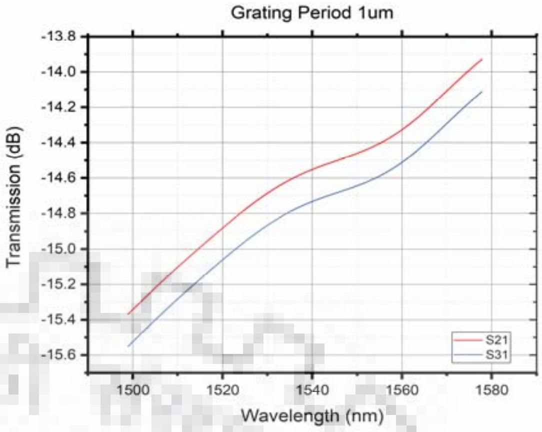


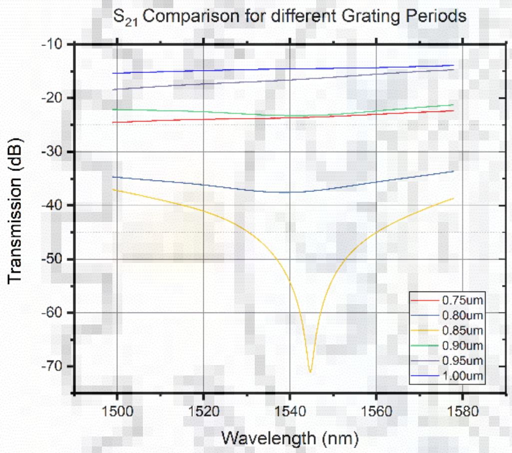
Grating Period 0.85um



Grating Period 0.90um





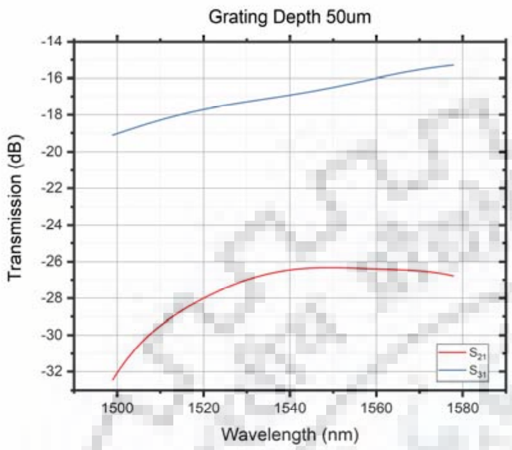


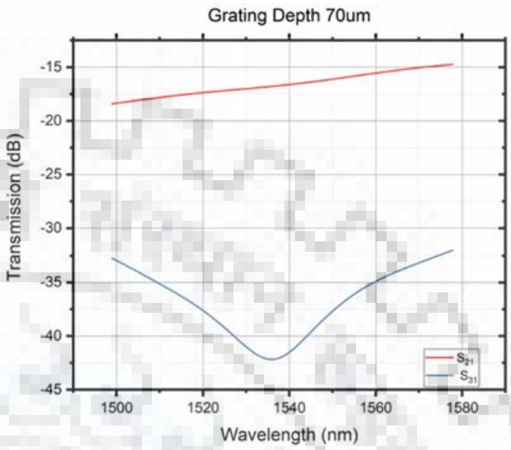
Interpretation

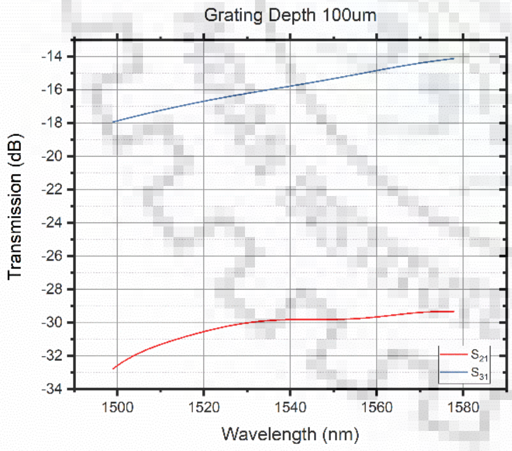
The two specifications for grating include directionality and efficiency which depend on structure and material. Keeping the material constant, the grating period and grating depth were varied.

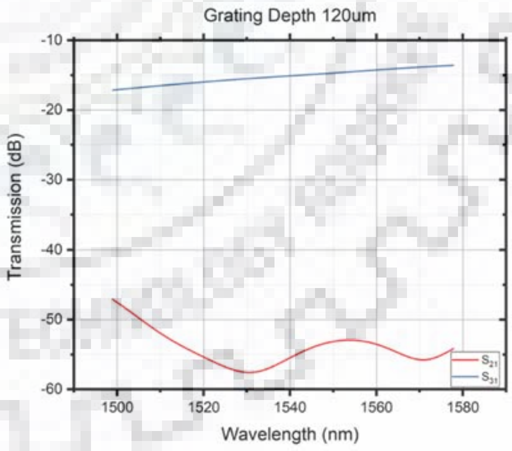
Increasing the grating period, increased the grating efficiency but compromised the directionality of grating. Thus, there is an optimum value for which both efficiency and directionality have significant values.

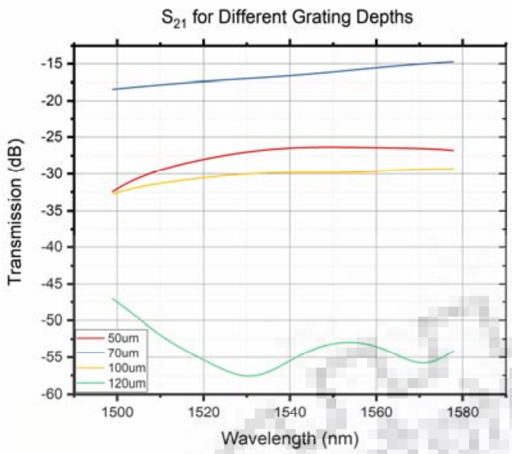
4.2.2 Grating Depth Variation

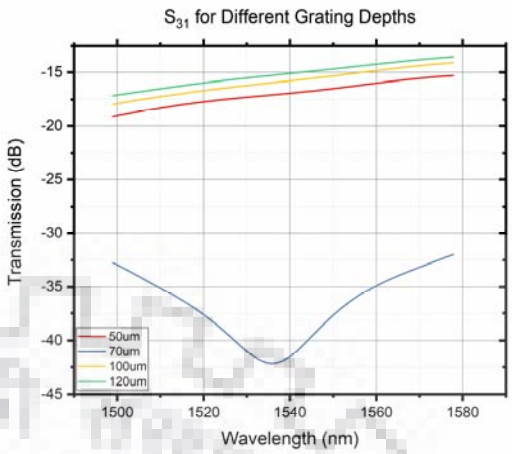












The simulation results indicate that as the depth of linear grating was increased, the efficiency was not affected significantly but directionality changes with change in grating depth as shown in the above graphs.

4.3 Straight Taper

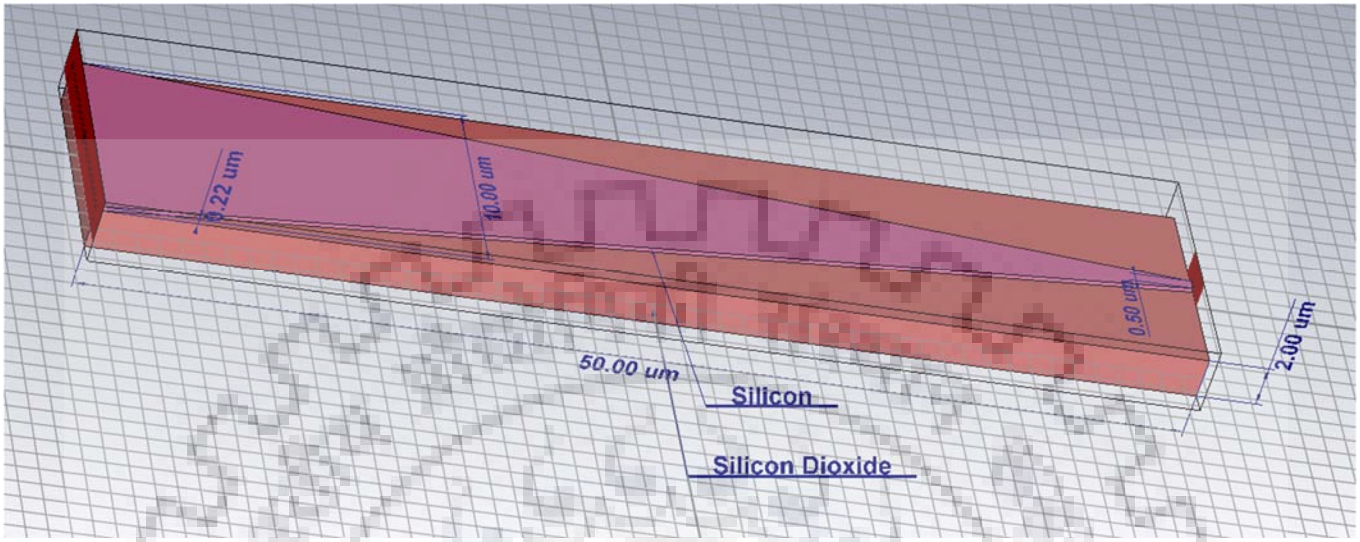


Figure 6(a): Straight Taper

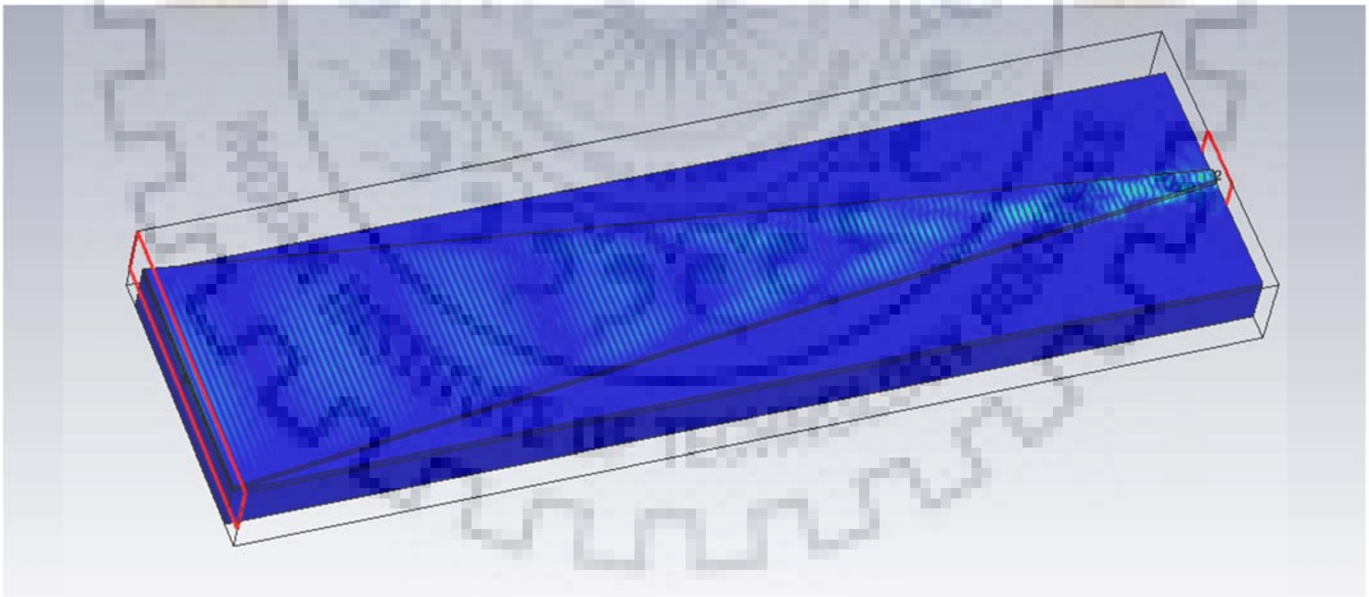
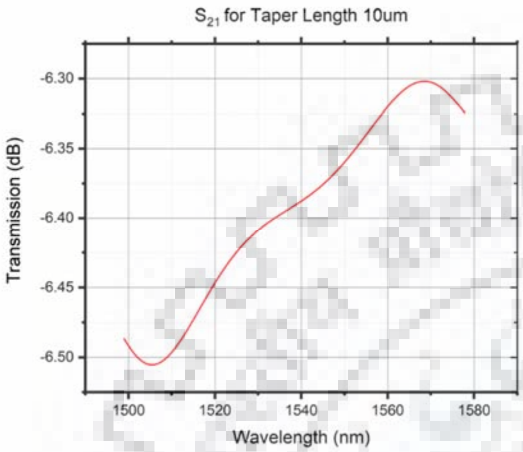
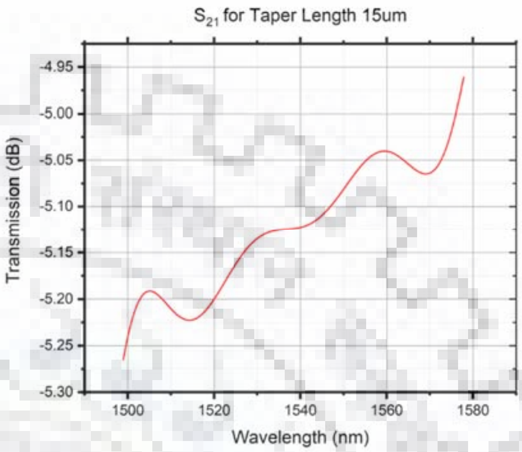


Figure 6(b): Simulation Structure of Straight Taper

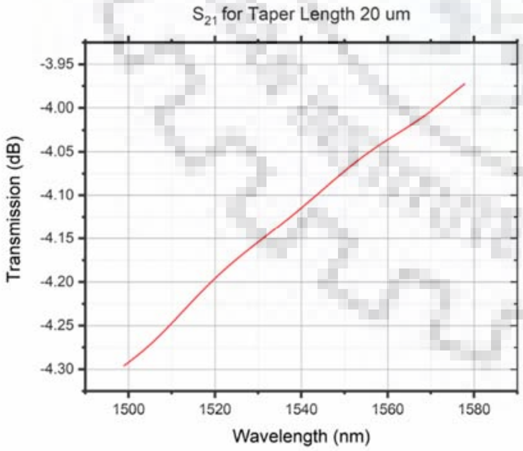
4.3.1 Taper Length Variation



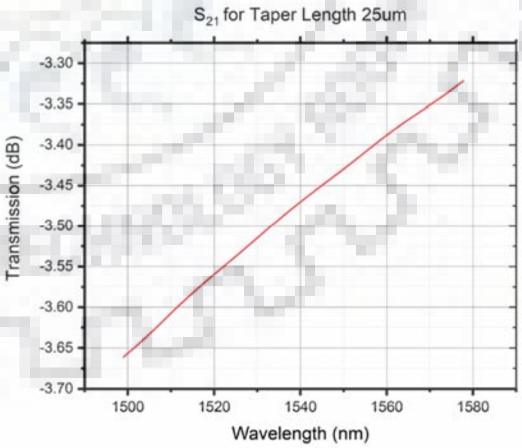
S_{21} for Taper Length 10um



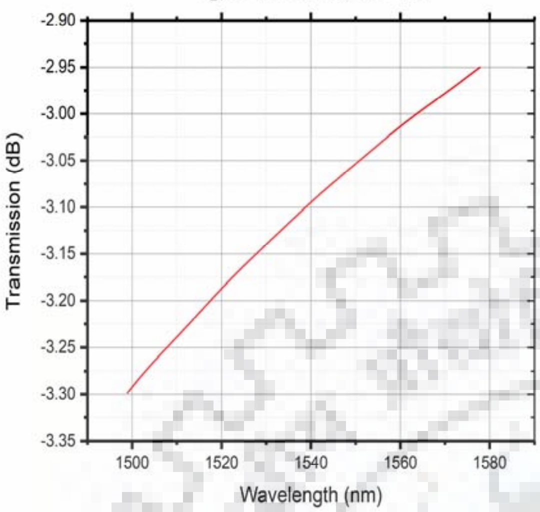
S_{21} for Taper Length 15um

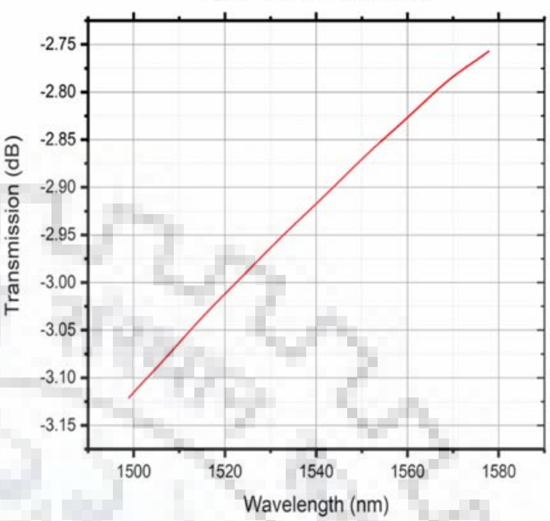


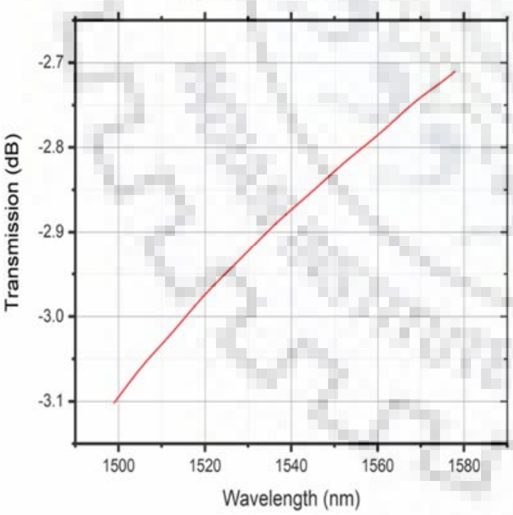
S_{21} for Taper Length 20 um

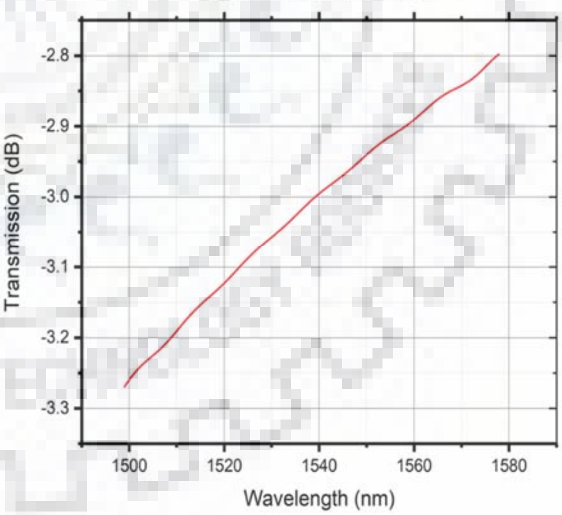


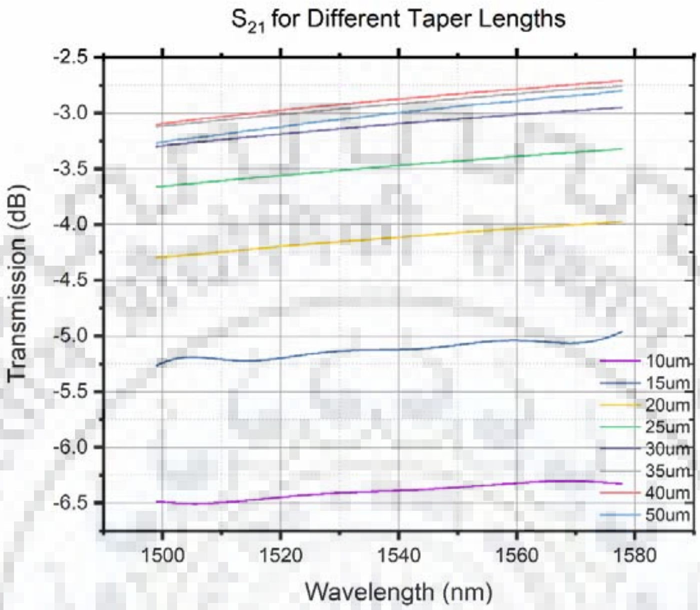
S_{21} for Taper Length 25um


S$_{21}$ for Taper Length 30 um


S$_{21}$ for Taper Length 35 um


S$_{21}$ for Taper Length 40 um


S$_{21}$ for Taper Length 50um



The straight tapered waveguide was designed with different lengths and simulation results were compared. The transmission through the tapered waveguide increased with the length as the length was increased from 10um to 40um but further increase in length from 40um to 50 um did not affect the transmission significantly although it did decrease slightly.

4.4 Linear Grating with Fibre

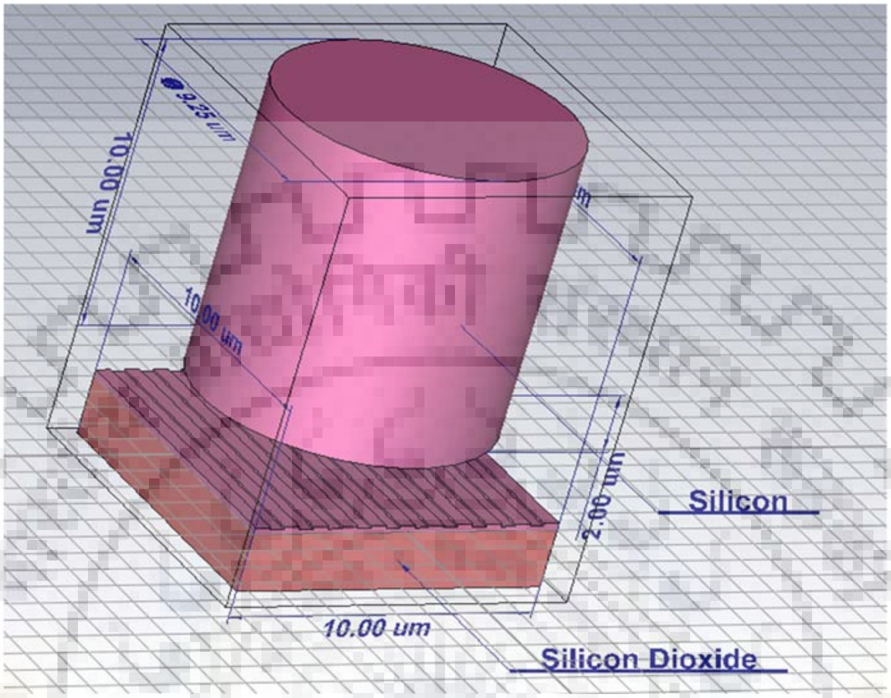


Figure 7(a): Linear Grating with Fibre

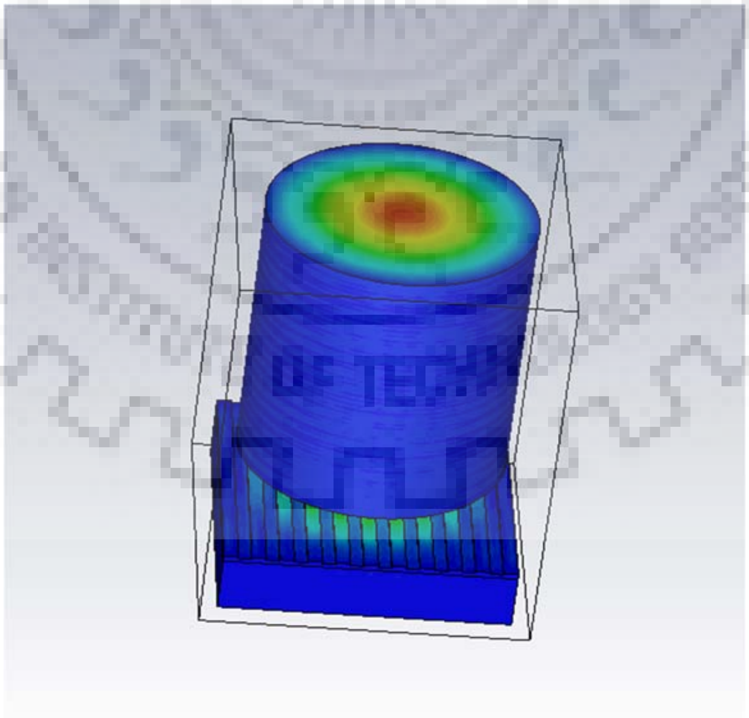
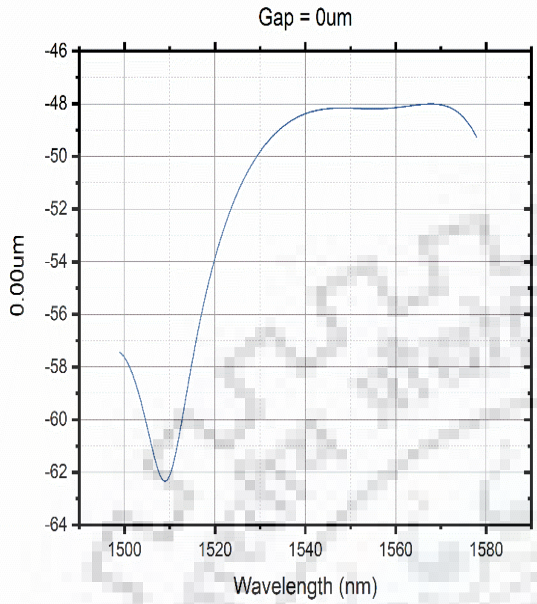
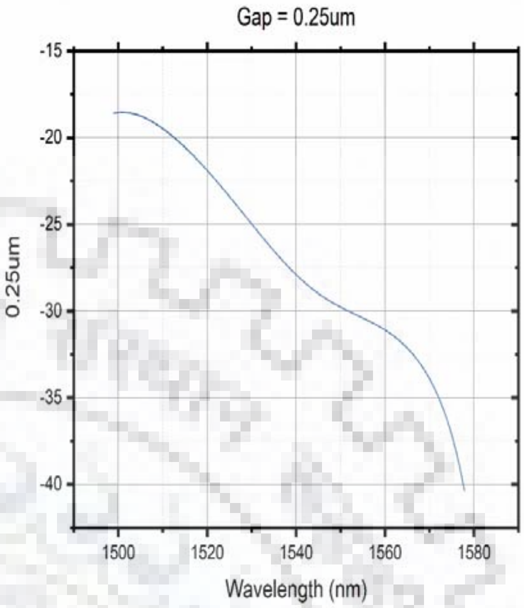
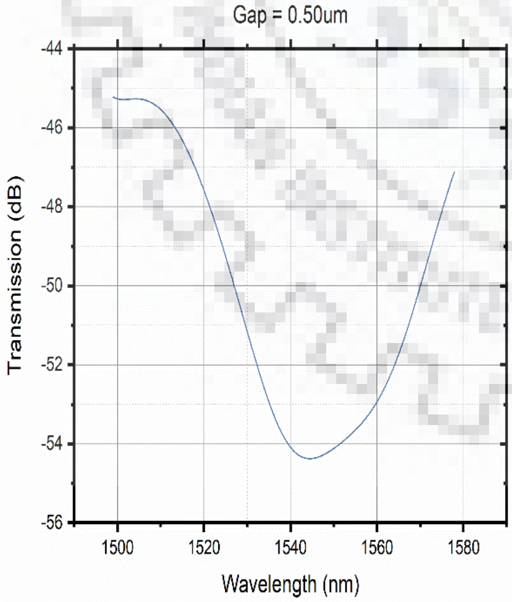


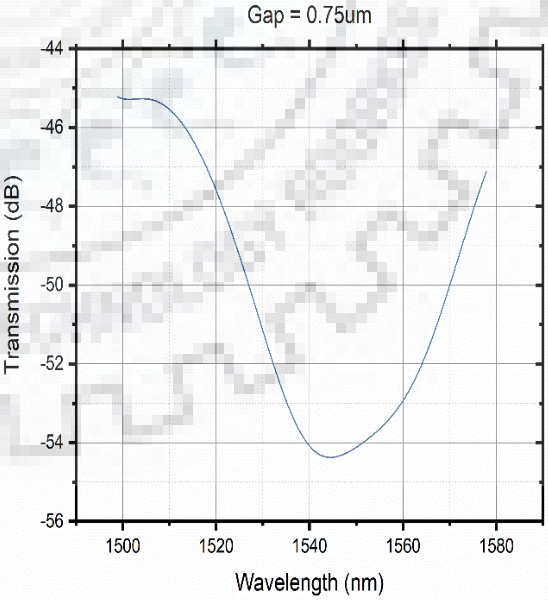
Figure 7(b): Simulated Structure of Linear Grating with Fibre

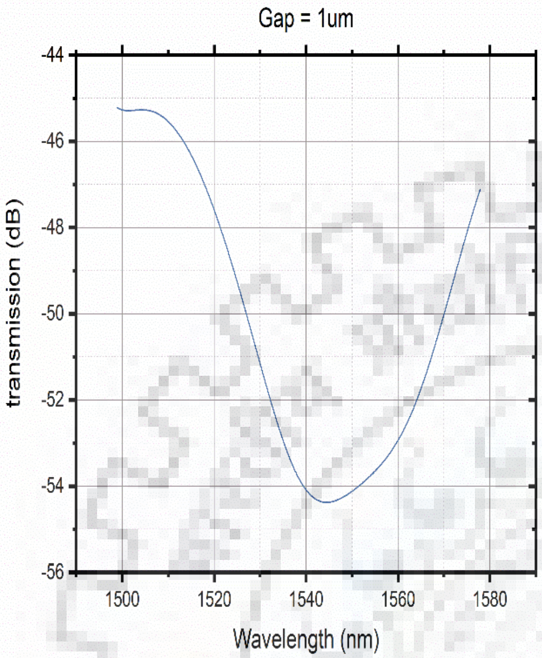
4.4.1 Variation of Gap between Fibre and Grating

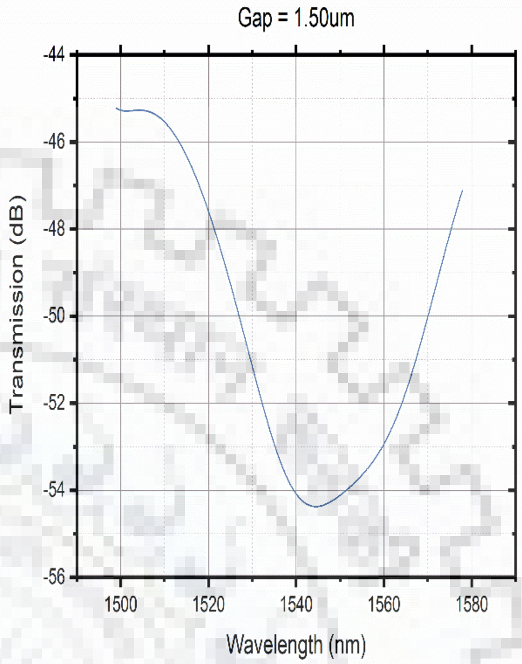


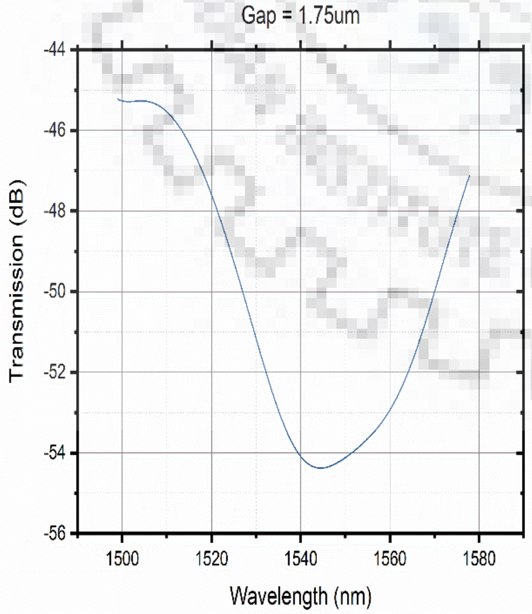


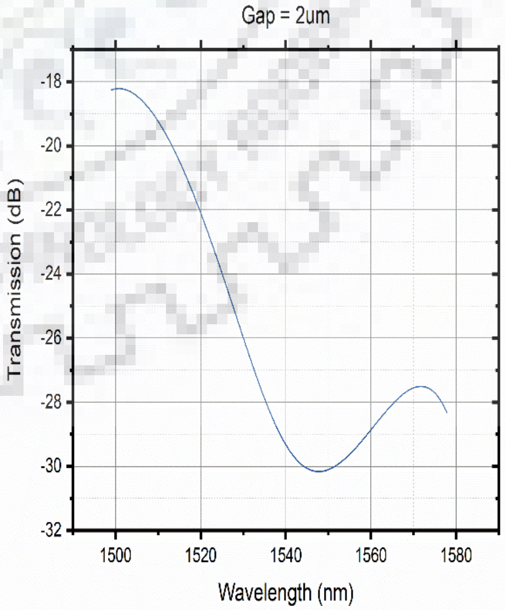


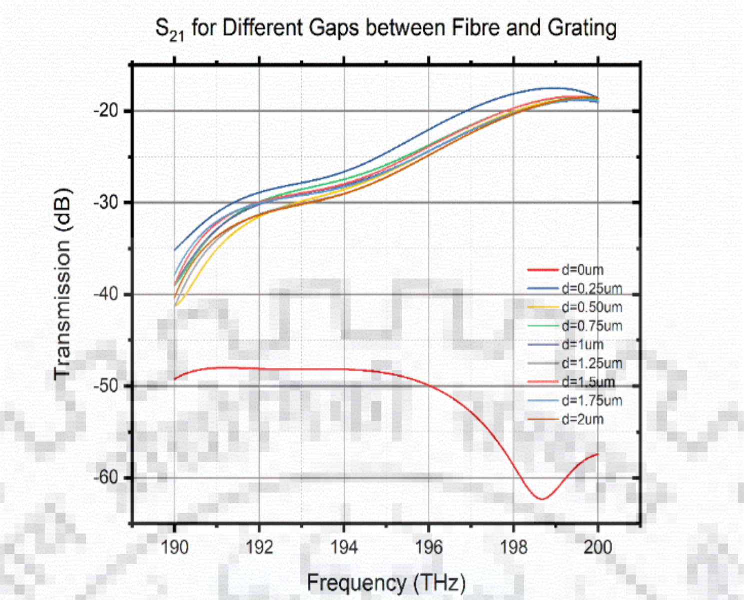



Gap = 1um
transmission (dB)
-44
-46
-48
-50
-52
-54
-56
1500
1520
1540
1560
1580
Wavelength (nm)


Gap = 1.50um
Transmission (dB)
-44
-46
-48
-50
-52
-54
-56
1500
1520
1540
1560
1580
Wavelength (nm)


Gap = 1.75um
Transmission (dB)
-44
-46
-48
-50
-52
-54
-56
1500
1520
1540
1560
1580
Wavelength (nm)


Gap = 2um
Transmission (dB)
-18
-20
-22
-24
-26
-28
-30
-32
1500
1520
1540
1560
1580
Wavelength (nm)



The combination of interfacing linear grating and fibre was designed and simulated for variable depths between the two starting from zero gap to 2um gap in steps of 0.25 um. The transmission increased significantly when the gap was increased from zero to 0.25 um but further increase did not change transmission significantly, although decreased it slightly from that at 0.25 um and further increases lead to very slight changes in either direction with no significant effect.

4.5 Linear Grating with Straight Tapers

4.5.1 Linear Grating with Smooth Taper

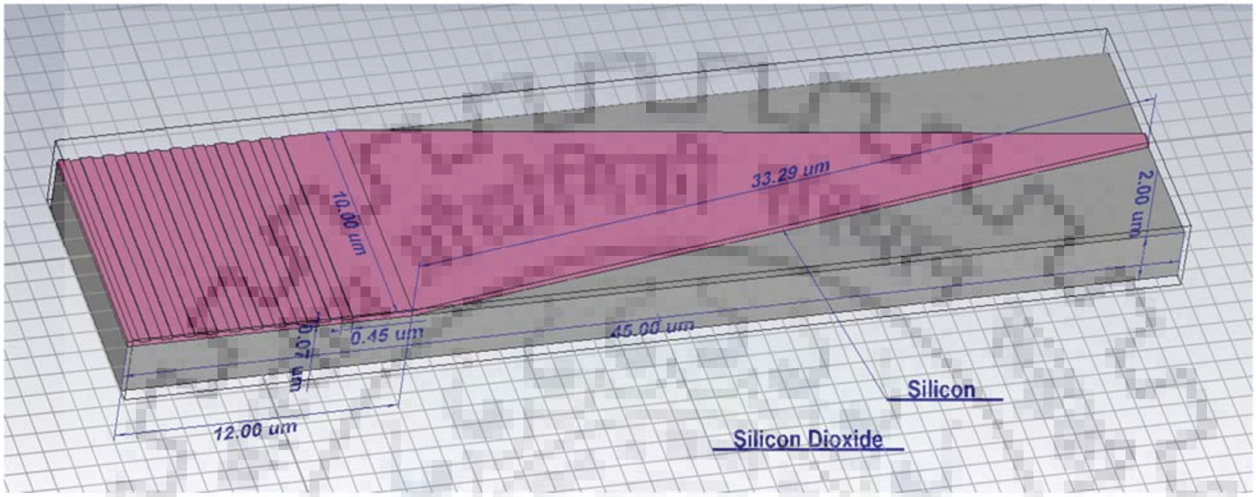


Figure 8(a): Linear Grating with a Smooth Taper

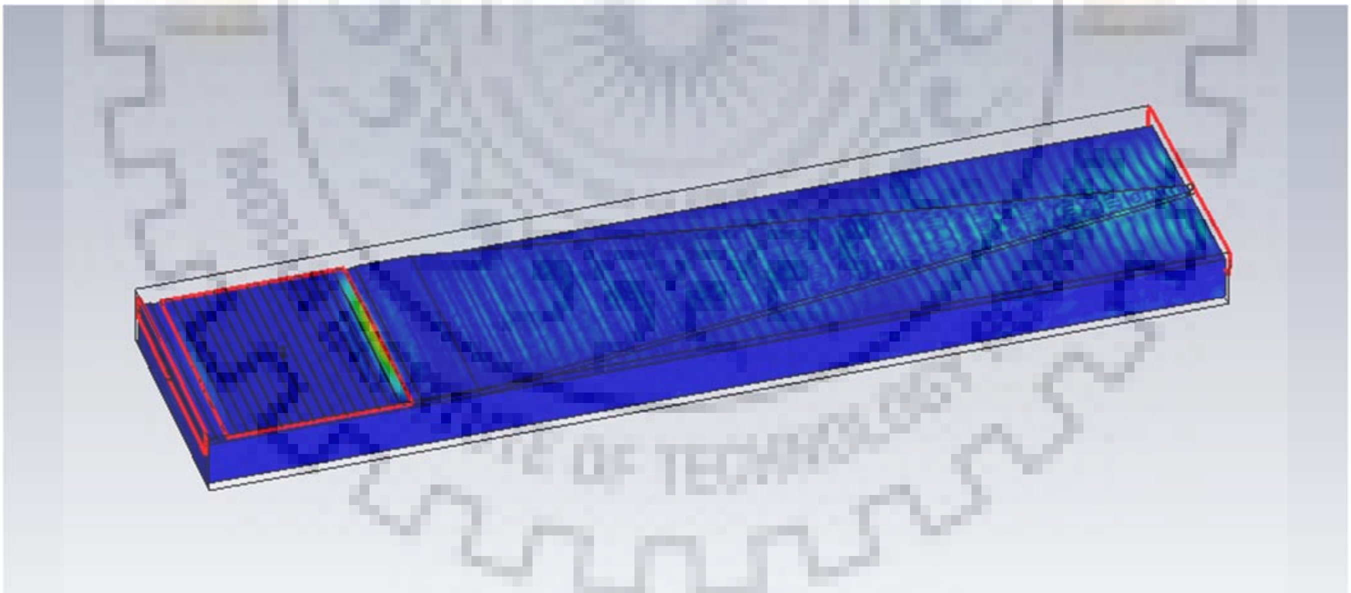


Figure 8(b): Simulation Structure of Linear Grating with a Smooth Taper

4.5.2 Linear Grating with Sectional Taper

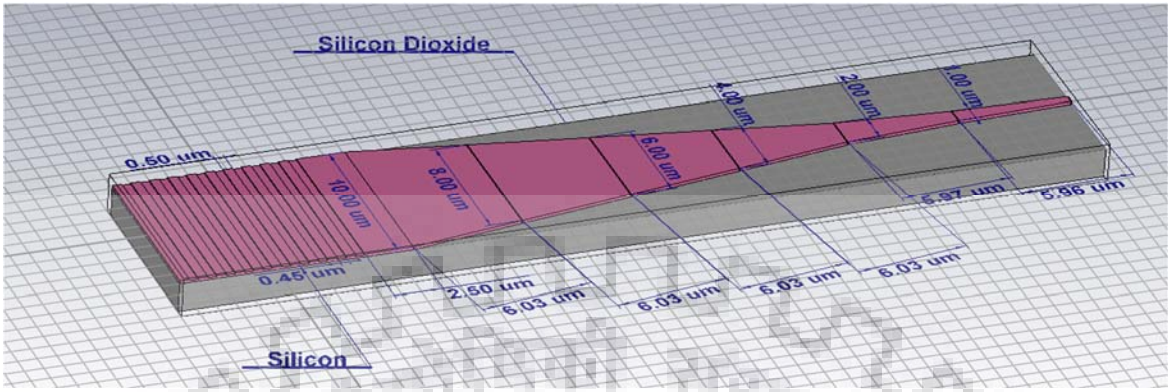


Figure 9 (a): Linear Grating with a Sectional Taper

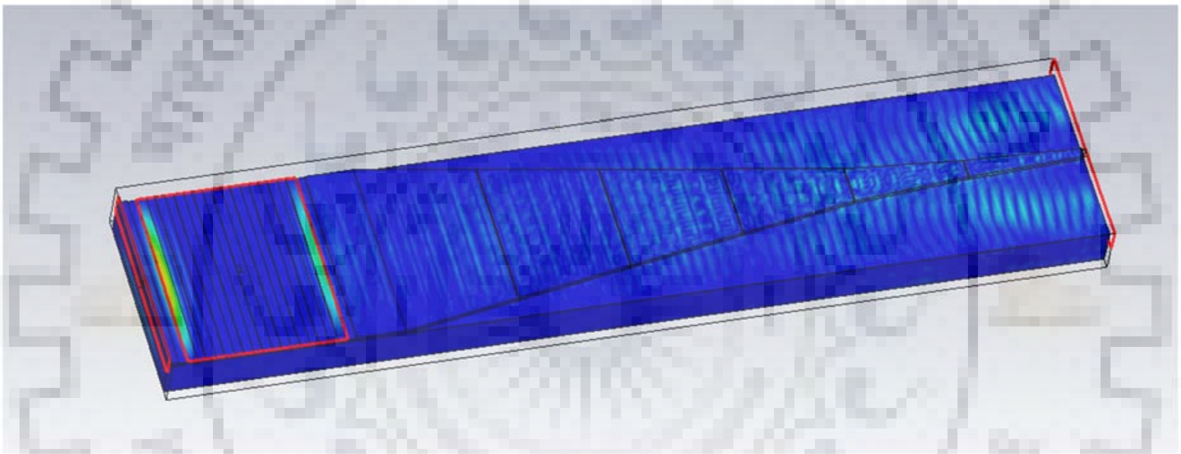
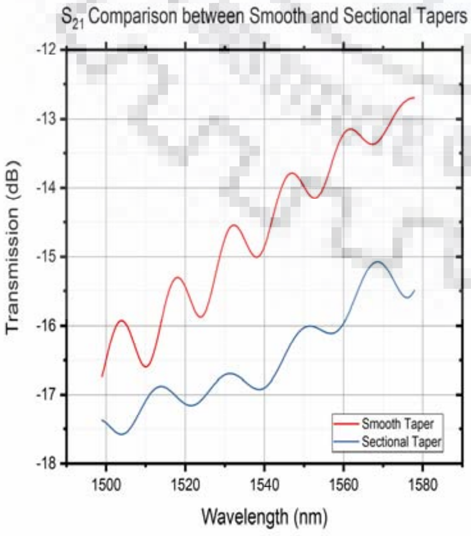
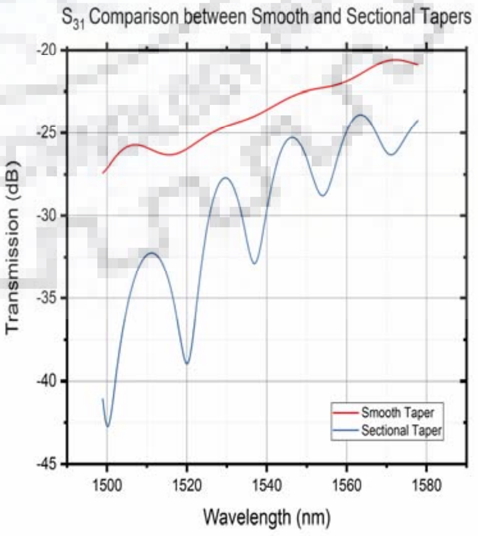


Figure 9 (b): Simulation Structure of Linear Grating with a Sectional Taper





4.5.3 Linear Grating with Smooth and Sectional Tapers

4.5.3.1 Linear Grating with 2 Smooth Straight Tapers

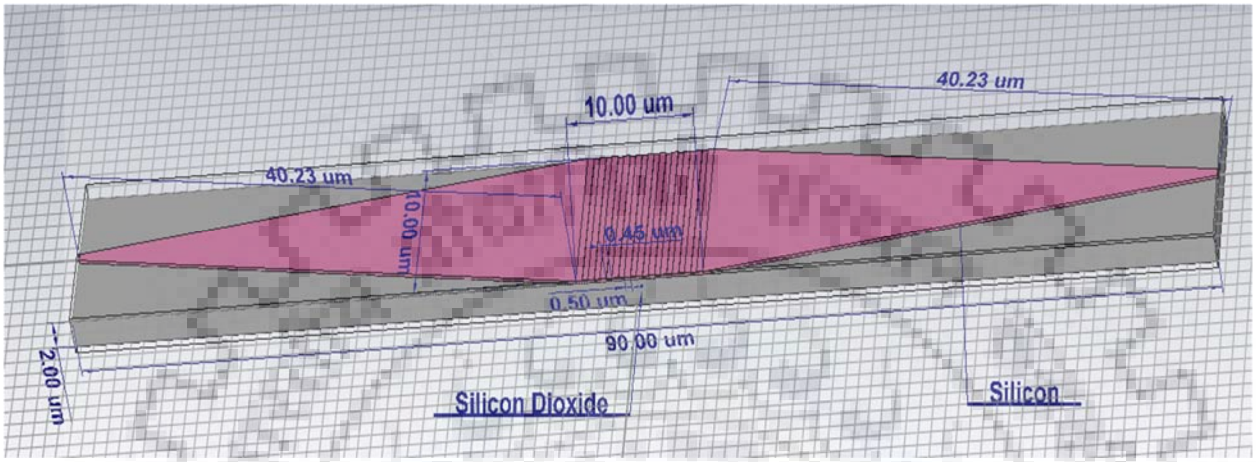


Figure 10(a): Linear Grating with 2 Smooth Tapers

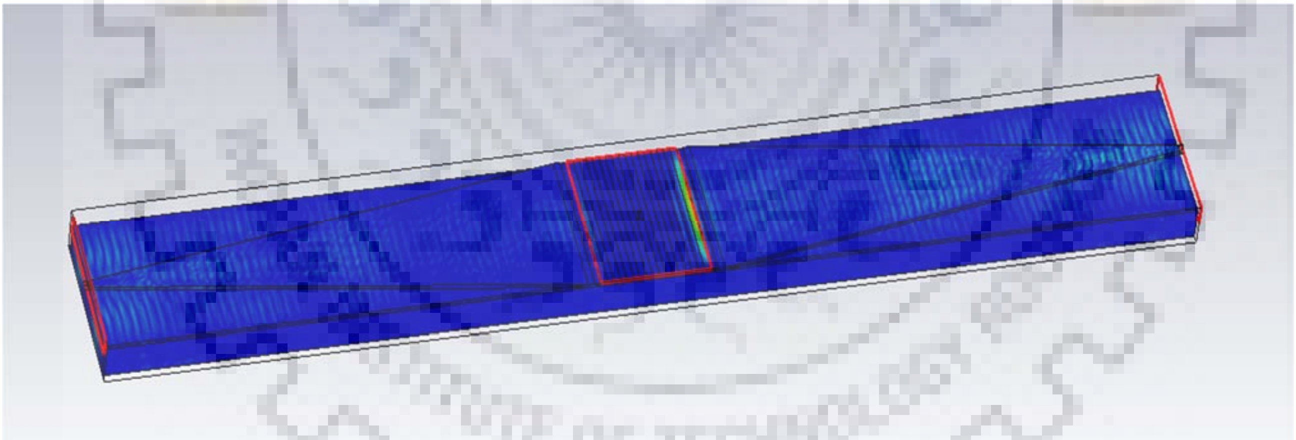
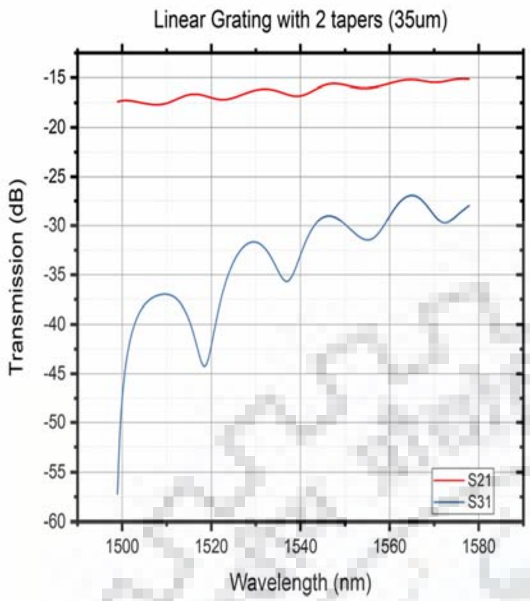
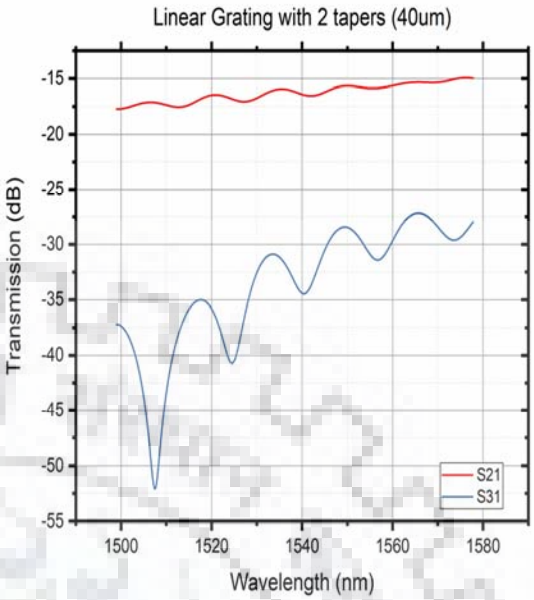
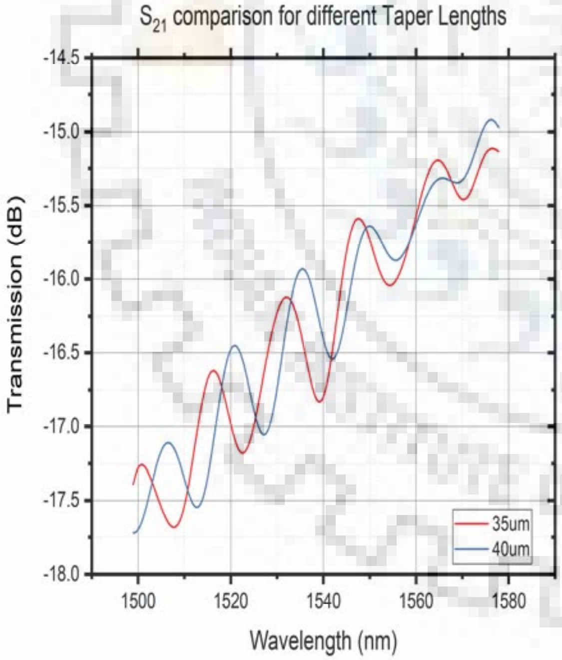
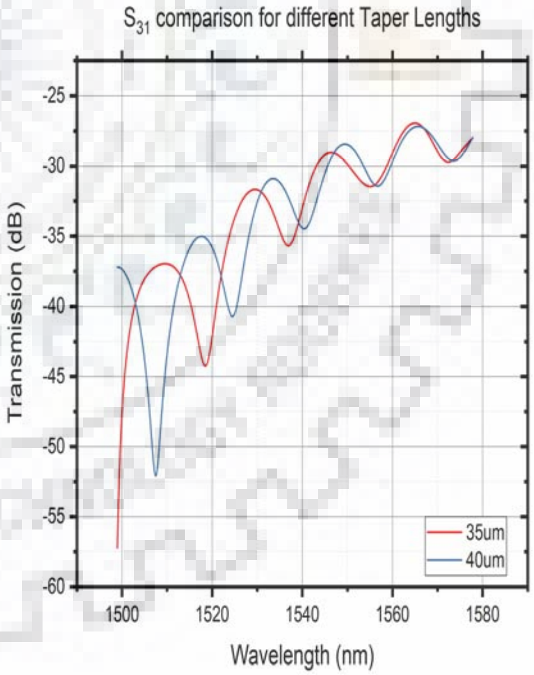


Figure 10(a): Simulation structure of Linear Grating with 2 Smooth Tapers


Linear Grating with 2 tapers (35um)


Linear Grating with 2 tapers (40um)


S_{21} comparison for different Taper Lengths


S_{31} comparison for different Taper Lengths

4.5.3.2 Linear Grating with both Smooth and Sectional Tapers

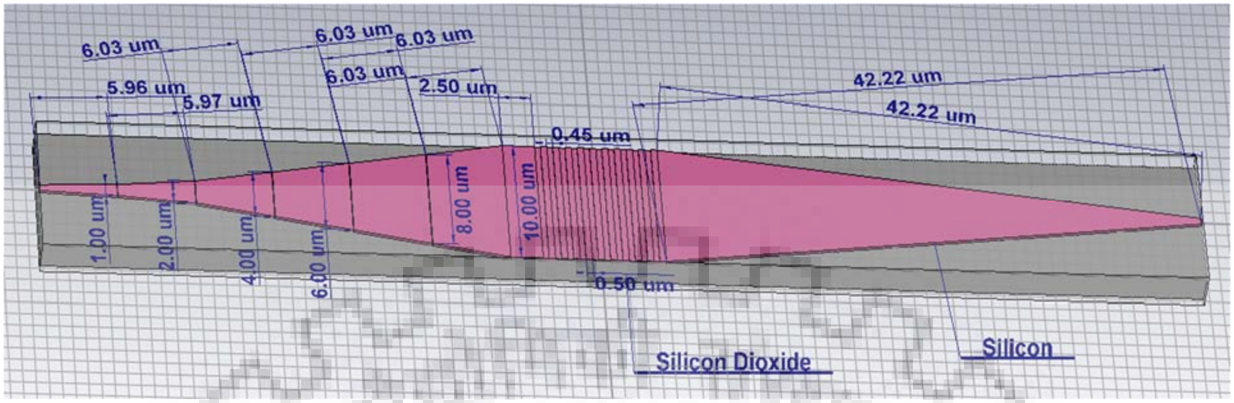


Figure 11(a): Linear Grating with both Smooth and Sectional Tapers

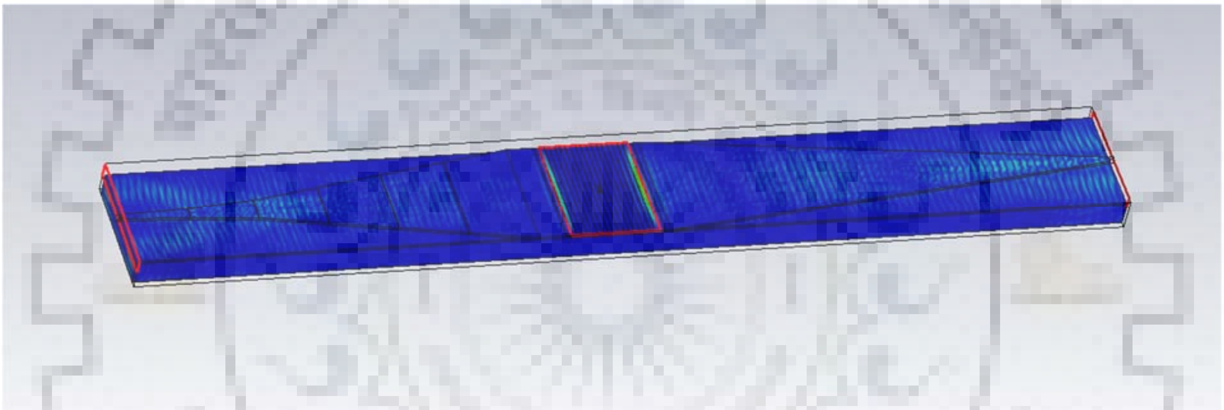
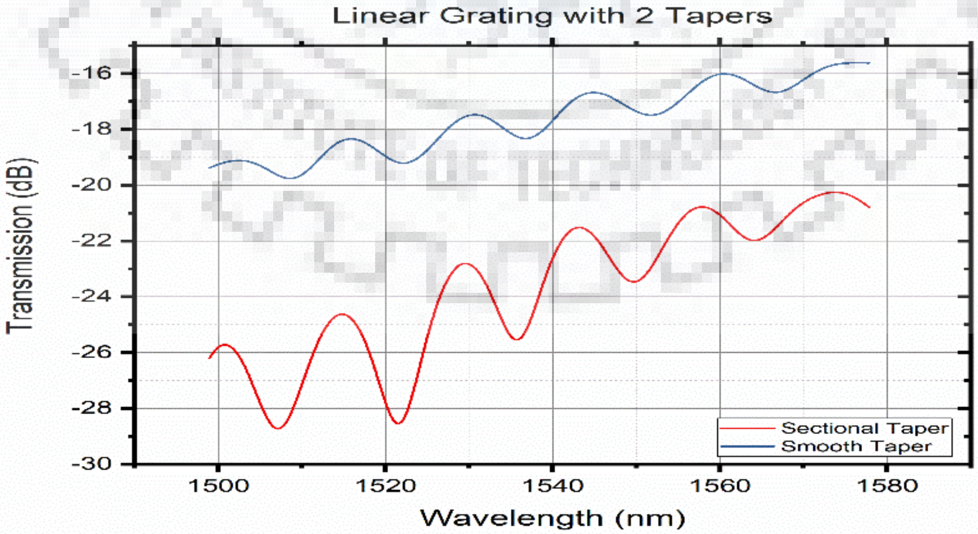


Figure 11(b): Simulation Structure of Linear Grating with Smooth and Sectional Tapers



The linear grating was designed with interfacing straight taper waveguide. First, a smooth straight taper was added to the grating and then a sectional straight taper waveguide added. The results showed that not only the transmission is more in case of smooth taper but also the directionality is lost in case of sectional taper. Further, tapers were added on either side of the linear grating. In case of adding 2 smooth tapers, the transmission takes place preferably in one direction due to directionality provided by the grating. However, in case of 1 smooth taper 1 sectional taper, the presence of sectional taper results in loss of directionality and transmission decreases as well.

4.6 Straight Taper with Single Mode Waveguide

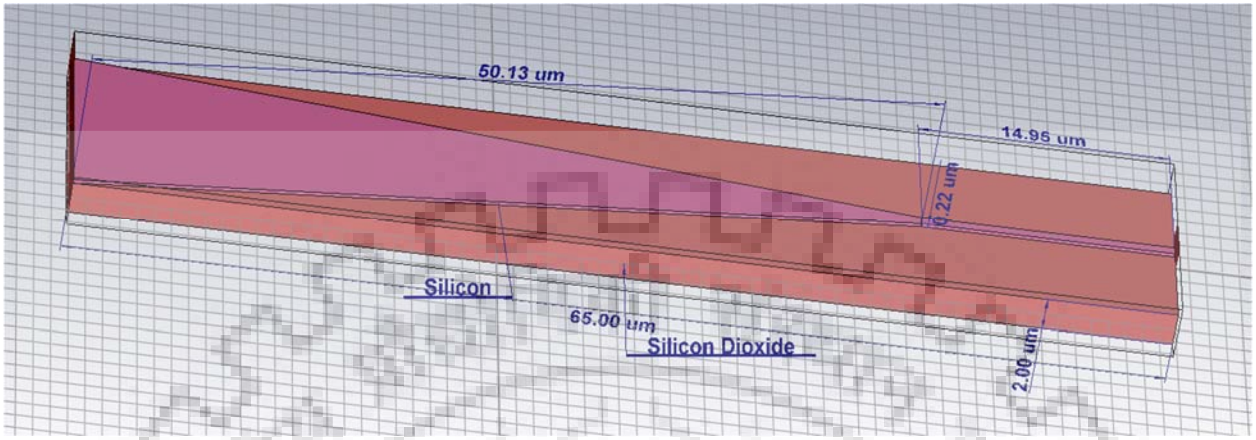


Figure 12(a): Straight Taper with Single Mode Waveguide

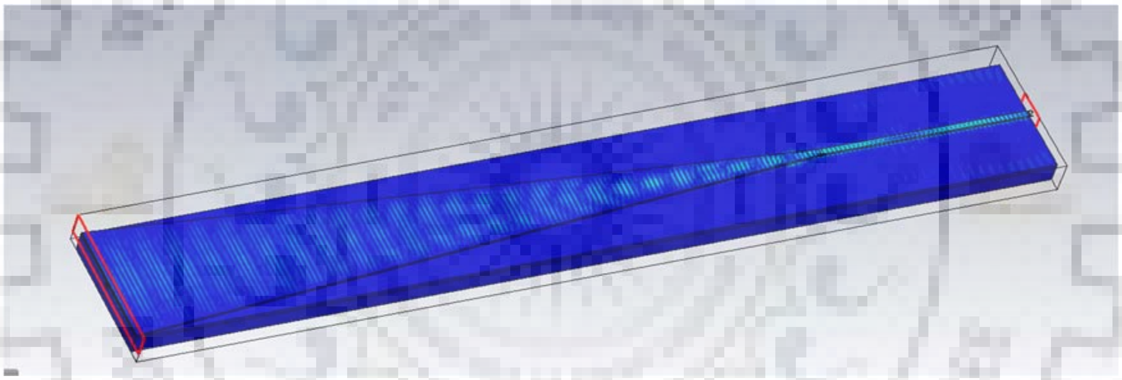
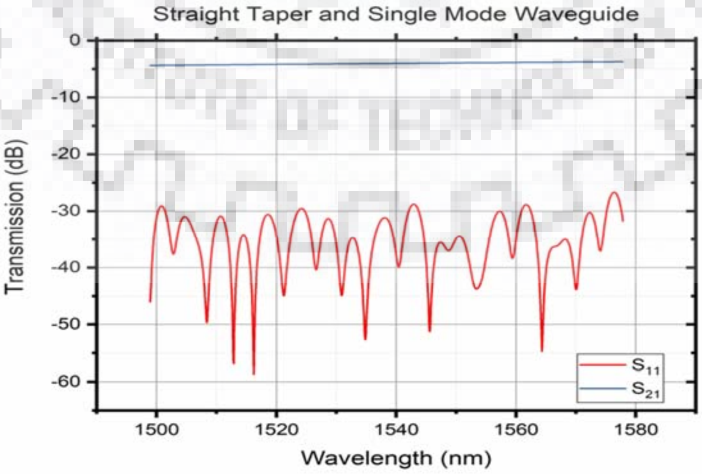


Figure 12(b): Simulation structure of Straight Taper with Single Mode WG



The combination of interfacing single mode waveguide and straight taper waveguide was designed and simulated. The results of simulations indicated strong coupling between the two interfacing components with most of the light getting transmitted through the waveguides with very little back reflection.

4.7 Linear Grating with Straight Taper and Single Mode Waveguide

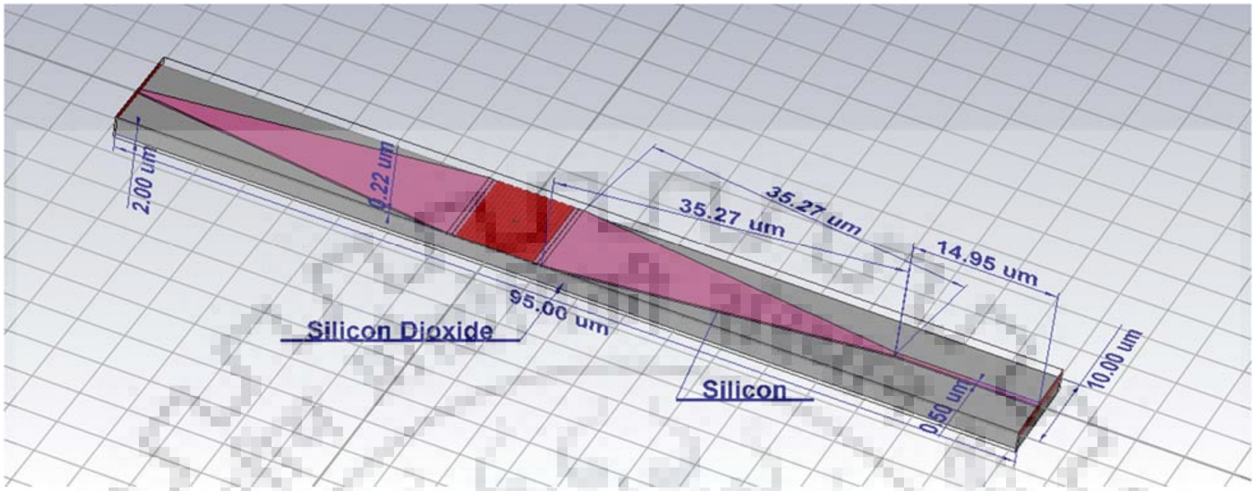


Figure 13(a): Linear Grating with Straight Taper and Single Mode Waveguide

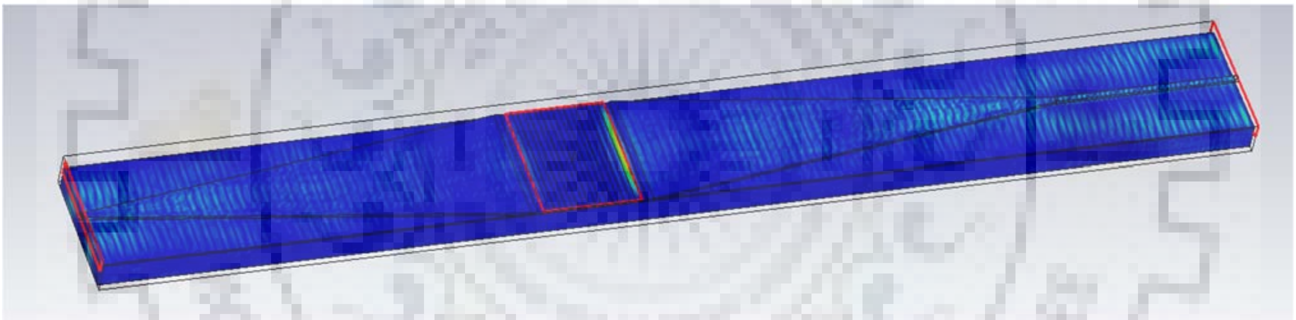
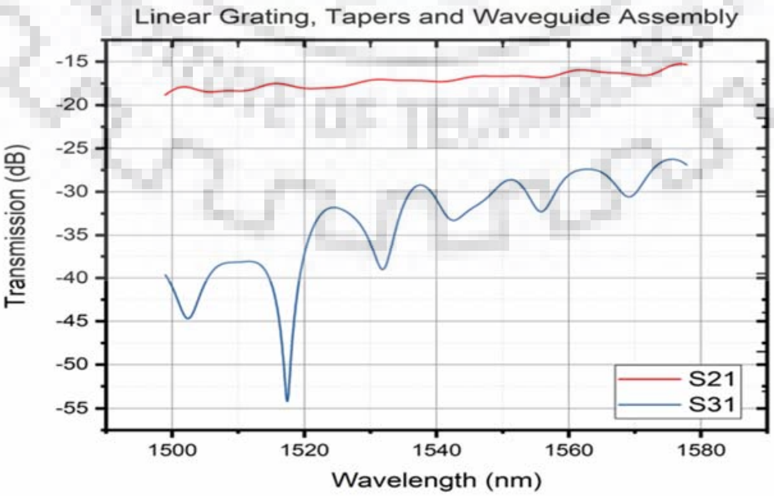


Figure 13(b): Simulation Structure of Linear Grating with Straight Taper and Single Mode WG



The assembly of linear grating with straight taper waveguides on either side of grating and a single mode waveguide on 1 side was designed and simulated. The results showed efficient transmission taking place preferably in one taper owing to the directionality provided by the linear grating and in turn efficient coupling between that straight taper waveguide and the single mode waveguide with very little transmission in the opposite direction.

4.8 Linear Grating, Straight Taper, Single Mode Waveguide and Fibre Assembly

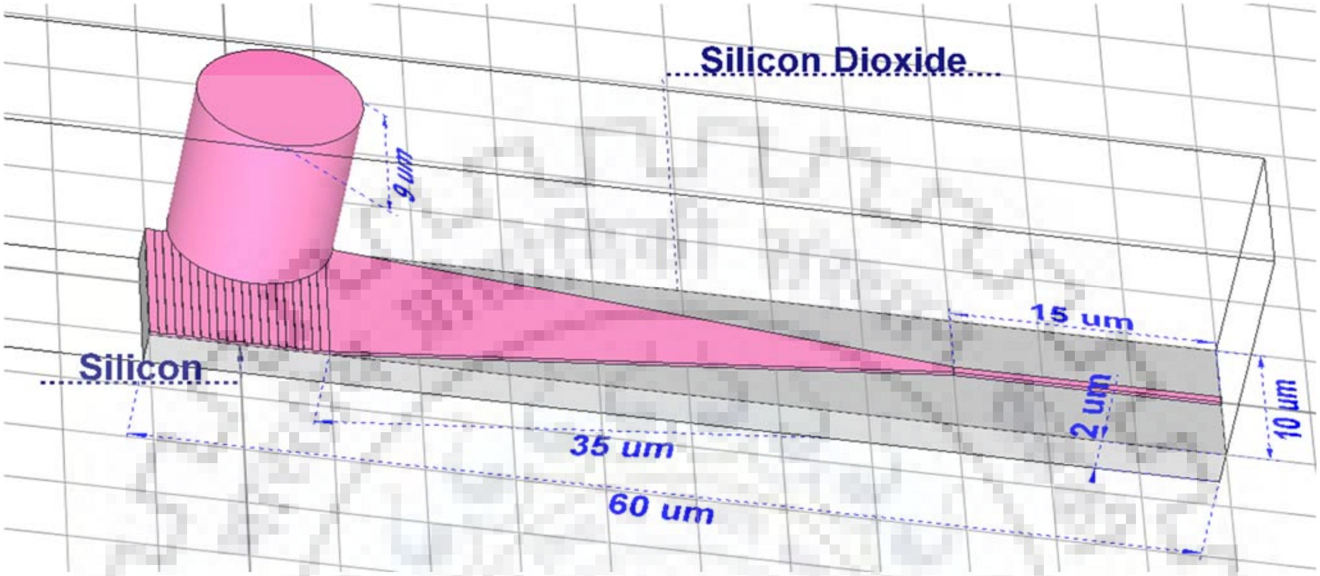
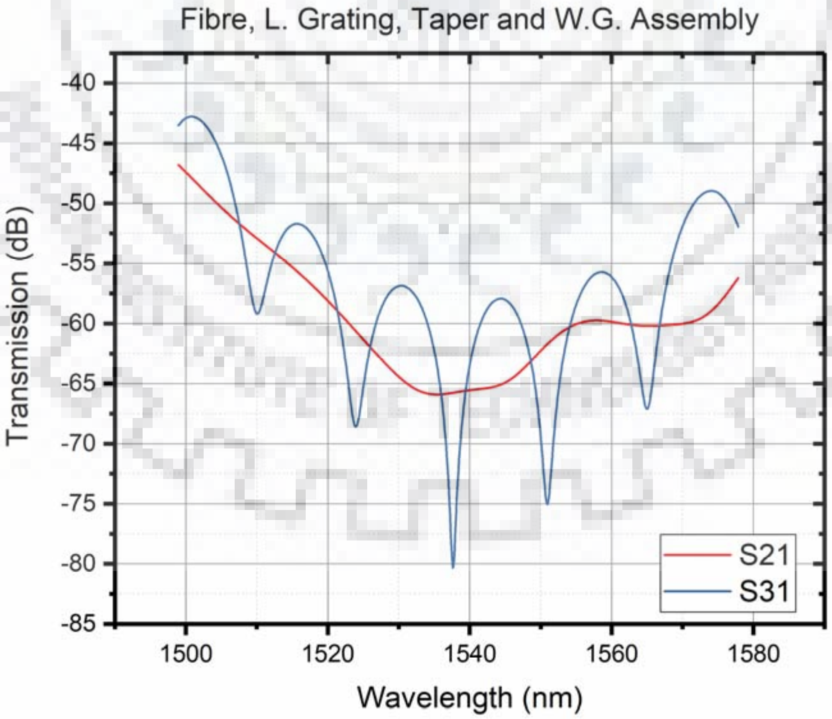


Figure 14: Linear Grating, Straight Taper, Single Mode Waveguide and Fibre Assembly



Finally the entire assembly all the interfacing components was designed results setup indicated laser transmission from fibre to Linear grating although whatever light was coupled into the linear grating was preferably directed into the straight taper waveguide and in turn the single mode waveguide. But effective coupling between the fibre and linear grating, it is advisable to explore different angles between the fibre and excess of linear grating.

Chapter 5: Conclusion

The aim was to design a Photonic Integrated Circuit. The various components included a Fibre, Linear Grating, Straight Taper and Single Mode Waveguide. In this setup, light is launched in through the fibre and gets directed out through the single mode waveguide. The linear grating serves the purpose of directing the light coming in through the fibre in certain directions. The straight taper serves as a bridge to fill in the dimensional gap between the grating and the waveguide.

1. **Linear Grating:**

   The functional efficiency of the linear grating depends on its structural parameters including the grating period and grating depth. These two parameters were varied one by one.

   (i) The results indicated that although transmission increases with grating period, directionality is compromised. The change in grating period changes diffraction orders thus affecting the directionality. Hence, an optimum value gives both high transmission and desired directionality.

   (ii) Increasing grating depth doesn't significantly affect the overall transmission but it significantly affects the directionality. Different grating depths result in light getting directed into different diffractive orders and thus different directions.

2. **Straight Taper:**

   The simulation results for straight taper with varying lengths showed that initially, increasing the length of taper significantly increases transmission. Then, further increase in taper length increases transmission but by lesser degree and at an optimum length, maximum transmission is achieved after which further increase will decrease.

3. **Grating and Fibre:**

   The coupling of light was analysed for a setup of linear grating and optical fibre by varying the gap between them. Initially, there was no gap at all between the grating and the fibre which resulted in negligible transmission. Then, the gap was increased in steps of 0.25um. The transmission increased by great degree in the first step of increasing the gap from zero to 0.25um but after that, increasing the gap did not affect the transmission significantly, yet decreases it slightly.

4. **Shape of Taper:**
   The setup of a grating with two tapers on either side was simulated to understand the effect of shape of taper on transmission. When two smooth tapers were used on either side of the grating, the light was directed preferably into one side, similarly, as in the presence of a single taper. However, if one taper is smooth and other tapers in sections, the light gets directed preferably into the smooth taper. Using single taper with the grating showed that the transmission is higher for the smooth taper and the losses in the sectional taper are much higher as compared to the smooth taper.

5. **Grating, Taper, Waveguide and Fibre Assembly:**
   Using the individual components resulting in maximum transmission, the entire setup was designed. The light is launched in through the fibre and comes out through the single mode waveguide after getting preferentially directed by the grating through the straight taper from where it enters the waveguide.

Future Scope

Though the assembly depicts the path of the light and results in transmission, there is huge scope for improvement. One such aspect could be the angular variation between fibre and grating which was fixed in this setup. Further, although linear binary grating effectively direct light, blazed gratings can be promising for this purpose. Moreover, the shape of taper can be varied to explore the best shape giving highest transmission.

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