Chapter

1

Introduction
1.1 Background

Understanding and controlling the interaction between light and matter is of fundamental importance to a wide range of subjects in science and technology. Over the last century extensive researches on this particular field of science has led to innumerable developments in physics including the birth of Quantum Mechanics and discovery of LASER.

One of the thrust areas of research today is to concentrate, focus, guide and route optical signal in the smallest possible physical dimensions to realize the nano-scale sized optical components and circuitry. The fundamental difficulty arises due to classical 'diffraction limit' which dictates a limitation on the transverse dimension of any optical component - it should be of the order of \( \lambda/2n \), where \( \lambda \) is the wavelength of the light and \( n \) is the refractive index of the medium. This length scale also governs the smallest distance between two points which can be resolved in an optical microscope. Light can be engineered beyond the diffraction limit by making use of light-matter interaction at a metal surface utilizing a long known theory that any interface between two media having dielectric permittivities of opposite signs of their real parts can support propagation of surface electromagnetic waves, whose fields decrease exponentially into both adjacent media away from the interface.

When we consider the interaction between metals and light, it is known that for frequencies up to the visible part of the spectrum metals are highly reflective and do not allow electromagnetic waves to propagate through them. Metals are therefore natural choice for deployment as the cladding layers for fabricating waveguides and resonators for electromagnetic radiation at microwave and far-infrared frequencies. In this low-frequency regime, the perfect or good conductor approximation of infinite or fixed finite conductivity is valid for most applications. In this frequency range only very small fraction of the impinging light penetrates into the metal. As the frequency increases towards the near-infrared and visible part of the spectrum, field penetrates significantly into the metal and thereby causing increased heat dissipation or loss. Finally, at ultraviolet frequencies, metals acquire dielectric characteristics and allow the propagation
of electromagnetic waves with certain amount of attenuation depending upon the electronic configuration and band structure of the metal. While the Alkali metals exhibit an ultraviolet transparency, noble metals such as gold or silver show strong absorption in this frequency regime.

The dispersive properties of metals can be described using a complex dielectric function \( \varepsilon(\omega) \), \( \omega \) being the angular frequency of the interacting electromagnetic wave. The optical properties of metals have been studied using Drude's model for a free electron gas [1] and are known to exhibit a negative real part of permittivity at optical frequencies [2, 3, 4]. Many experimental as well as theoretical studies based on classical electron theory yield an equivalent negative dielectric constant for many metals when excited by an electromagnetic wave at or near optical wavelengths [5, 6]. This property allows the metal-dielectric interface to support a surface Plasmon Polariton (SPP) mode which is basically a surface electromagnetic wave that has greater momentum than light of the same frequency and remains bound to the interface through coupling of electromagnetic waves to oscillations in conduction electrons in the metal. Surface Plasmon Polaritons (SPPs) are transverse magnetic (TM) polarized optical surface waves which propagate, typically, along a metal-dielectric interface [7, 8, 9]. Totally bound non-radiative SPP mode is supported by this structure having the maximum of the fields at the interface, decaying exponentially away from the interface in both the media. According to classical or Drude's model, the complex relative permittivity of the metal region is given by the well-known plasma frequency dispersion relation

\[
\varepsilon(\omega) = \left(1 - \frac{\omega_p^2}{\omega^2 - j\Gamma \omega}\right) \quad (1)
\]

Where \( \omega \) is the excitation frequency, \( \omega_p \) is the electron plasma frequency, \( \omega_p^2 = \frac{n e^2}{m \epsilon_0} \) (\( n \) = electron density in the metal, \( e \) is electronic charge, \( m \) is the effective mass of the electron and \( \epsilon_0 \) is the permittivity of the free space) and \( \Gamma \) is the scattering rate which accounts for the dissipation through scattering of electron motion in metal. \( \Gamma \) is also expressed as the reciprocal of \( \tau \), the relaxation time of the free electron gas in the metal, which is typically of the order of \( 10^{14} \) sec at room temperature. As an illustrative example we can
consider the case of silver, a noble metal having $\omega_p = 1.2 \times 10^{16} \text{ rad/sec}$ and $\Gamma = 1.45 \times 10^{13} \text{ sec}^{-1}$. The real part of $\varepsilon(\omega)$ determines the degree to which the metal polarizes in response to an applied external electric field and the imaginary part of $\varepsilon(\omega)$ quantifies the relative phase shift of this induced polarization with respect to the external field and it contributes to losses. In the visible and near infrared parts of the spectrum, we obtain a negative value of the real part of $\varepsilon(\omega)$ and this implies that surface plasmon polariton modes can be supported at the interface of the metal and a normal dielectric. For large frequencies close to $\omega_p$ ($\omega < \omega_p$), the product $\omega \tau \gg 1$ and $\varepsilon(\omega)$ becomes predominantly real and negative, and is expressed as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \tag{2}$$

Plasmons were first detected in the visible part of electromagnetic spectrum by Wood in an interesting experimental observation of intensity drops in the spectra of visible light reflected from a metal grating. The experiment was conducted in the year 1902 [10] but the contribution of plasmons to the intensity drops was not explained until 1941 [11].

The topic of surface plasmon polariton (SPP) has recently generated tremendous interest in scientific community for a variety of reasons. In part this is because of advances in nano-scale fabrication technologies that allow suitable sized structures to be made and explored as a way of harnessing SPPs [12]. The ability of surface plasmon polariton to beat the diffraction limit is a tremendous boon to technology and its usefulness towards achieving higher integration density in photonic integrated circuits is now well established [13, 14]. SPP based waveguides and the associated problems are a major branch of study particularly for nano-scale confinement of light with prospective technological applications in thermo-optic devices [15, 16, 17], electro-optic devices [18, 19], active structures [20, 21, 22], sensing [23, 24, 25, 26], imaging, all-optical signal processing and optical computing [27]. SPP based waveguides are also envisaged as one possible route in the development of sub-wavelength optics and photonic integrated circuits [28]. Tremendous efforts have been put by different research groups to develop nano-optical circuit components using the principle of SPP wave propagation [29].
Researchers have practically demonstrated various passive integrated structures for SPP guidance and routing. The key areas of technology likely to have significant developments based on Plasmonics are (a) the sensors capable of single molecule detection, (b) the optical microscopy with improved resolution, (c) Terahertz (THZ) spectroscopy and communication and (d) the all optical nano-circuits which will far surpass electrical circuits in terms of speed. Different modeling schemes based on numerical simulation techniques have also been proposed [30, 31, 32, 33]. However the electromagnetic waves associated with SPP modes have certain drawbacks, poor propagation length (typically about 10-100 µm in the visible and near-infrared spectral range), for example, which do not encourage practical applications and deployment. It is found that any attempt to improve the modal confinement in a SPP guide is always accompanied by increase in attenuation. High lateral field confinement is however necessary to inhibit crosstalk between closely packed waveguides so that these guiding devices can be integrated at high density in coplanar geometries. Considerable research activities have also been taken up to tackle the issue of loss (resulting in poor propagation length) in highly confined SPP modes to make the SPP waveguides suitable for development of nano-optic devices in practice. It has been proposed and demonstrated that loss parameters of SPP waveguides can be considerably improved and compensated by making use of gain media at strategic locations in the waveguide geometry [20, 21, 34, 35, 36, 37].

In the domain of both passive and active plasmonics, the studies on modal characteristics of surface plasmon waveguides have become extremely important and relevant. Well-confined wave-guidance and improved propagation length are the key aspects being addressed by the researchers. These goals in turn have led to a number of fascinating innovations in the SPP guiding structures.

1.2 SPP waveguides

As we see the recent developments of THz technologies [38, 39, 40] with applications as diverse as astronomy [41], medicine [42] or security [43] the general endeavour is to build compact THz circuits. This requires the design of THz waveguides carrying tightly
confined electromagnetic modes, preferably with subwavelength transverse cross section. Besides circuit integration and compact device design, sub-\(\lambda\) localization may be advantageous for THz time-domain spectroscopy [44] and non diffraction-limited imaging [45]. Though several structures have been put forward, none of them passes all the following requirements. First, structures should be easily manufactured and, if possible, planar and monolithic. Second, subwavelength transverse size is to be achieved. Finally, absorption and bend losses should be minimized. Another important design aspect is in/out couplers since they work as the interface to the surrounding photonic circuit components and systems. In this context, compact tapers able to laterally compress the modes down to the sub-\(\lambda\) level seem essential. With these requirements in mind it is illuminating to compare optical waveguides with those proposed for the THz range. Optical fiber modes exhibit a cut-off diameter such that fibers cannot be of subwavelength size and, moreover, modal size grows as this cut-off is approached. In the THz regime dielectric wires [46] meet the same limitation. The photonic crystal fiber approach [47] shares the inability of sub-\(\lambda\) confinement, and low-index discontinuity waveguides [48] perform better regarding modal size but are neither planar nor monolithic. Metals are an alternative when operating at optical frequencies because surface plasmon polariton (SPP) waves propagating on flat metal-dielectric interfaces provide subwavelength confinement in the direction perpendicular to the surface. This metallic route has been tried for the THz regime, but the corresponding EM modes, known as Zenneck or Sommerfeld waves, lose their confined character at these frequencies [49, 50]. The plasma frequency of metals is typically in the visible or ultraviolet part of the electromagnetic spectrum and the confinement of SPPs to the metal at low frequencies, i.e., at THz frequencies, is very weak, as the waves evolve from a confined SPP to a delocalized Sommerfeld-Zenneck wave. There are two ways by which the SPP confinement at THz frequencies can be increased. In the first approach the electromagnetic waves bound to metal surfaces that mimic surface plasmon polaritons (referred to as spoof SPPs) are obtained by perforating a flat metal surface periodically with holes and grooves. Geometrically-induced surface plasmons [51] supported by periodically corrugated metallic surfaces overcome the low localization of Zenneck
waves. A number of waveguiding structures based on this concept has been already suggested [52, 53, 54, 55], but they have failed to meet simultaneously all the above mentioned requirements. The other approach to increase THz SPP confinement is to use semiconductors instead of metals in surfaces, wires or particles where the plasmon modes can be excited. Semiconductors have a much lower plasma frequency than metals, typically in the mid-infrared, allowing the strong confinement of THz SPPs to their surface. Another advantage of semiconductors when compared with metals is that semiconductors are much more versatile materials since their plasma frequency, hence the properties of SPPs, are remarkably tunable.

Reviews of SPP waveguides can be found, for example, in [56, 57, 58]. The SPP waveguides can be broadly classified in two basic categories – one dimensional (1D) and two dimensional (2D). 1D waveguides are those which confine the electromagnetic field components in only one transverse direction whereas the 2D waveguides ensure confinement in both the transverse directions. Although the 1D-guides are of limited practical importance, a thorough understanding of the simple 1D-structures is very much essential for building up the concepts and developing the ideas for guidance, confinement, excitation and other propagation characteristics of optical signals in more complicated sub wavelength geometries. SPP waveguides should exhibit (i) useful subwavelength confinement, (ii) relatively low propagation loss, (iii) single mode operation and (iv) efficient transmission around sharp bends.

The schematic diagrams with brief introduction of commonly studied 1D and 2D SPP guides are furnished below along with the co-ordinate system. Z-direction is the direction of wave propagation.

(a) **Metal-Dielectric single interface waveguide**

![Figure 1.1](image)

Figure 1.1 Metal half space above a non dispersive dielectric half space.
Figure 1.1 schematically represents the fundamental SPP waveguide structure in 1D along with the coordinate system used in this chapter. The supported SPP mode is a TM type surface electromagnetic wave with no confinement in the X-direction. The confinement is achieved only in Y-direction with exponentially decaying fields on either side of the interface in both the metal and dielectric half spaces. Only a single SPP TM mode is supported in this structure with three non-zero field components \([E_y, H_x, E_z]\). The dispersion relation and other features of this simplest SPP waveguide are discussed in a subsequent section and also in chapter 2.

(b) Dielectric-Metal-Dielectric double interface waveguide

![Figure 1.2 Three layer dielectric-metal-dielectric SPP waveguide](image)

Figure 1.2 represents the schematic diagram of a three layer 1D SPP guide with a metal slab of infinite width and finite thickness sandwiched between two dielectric half spaces of different permittivity. This is an asymmetric structure. The structure becomes symmetric if the upper and lower dielectrics are identical. This structure is also called a D-M-D or I-M-I type where I or D stands for Insulator or Dielectric and M stands for Metal. Unlike Dielectric-Metal single interface SPP guide, two types of SPP TM modes are supported in a symmetric D-M-D structure. One is a symmetric mode having lower propagation loss and the other is asymmetric mode with relatively higher propagation loss. The symmetry/asymmetry is determined by profile of the dominant field component which is \(E_y\) in most of the 1D SPP waveguides. In case of a symmetric 3 layer structure \((\epsilon_{d1} = \epsilon_{d2})\) the modal symmetry (asymmetry) is determined by the presence of electric (magnetic) wall at the symmetry plane passing through middle of the metal layer. The symmetric mode is called a Long Range SPP (LRSPP) mode as it supports a longer propagation length compared to that of the asymmetric mode which is also called a Short Range SPP (SRSPP) mode. Both the modes are slow waves and do not exhibit any cut off
characteristics in respect of metal thickness. However if the structure is not symmetric, the LRSPP mode (and not the SRSPP mode) has a cut-off thickness of metal film below which the mode does not propagate. The LRSPP and SRSPP modes become degenerate at relatively larger values of metal layer thickness when two independent SPP modes propagate in the upper and lower metal-dielectric interfaces. The dispersion relation and other modal features of D-M-D type SPP waveguide are presented in chapter 2.

(c) Metal-Dielectric-Metal double interface waveguide

\[ \begin{array}{c}
\epsilon_m(\omega) \\
\epsilon_d \\
\epsilon_m(\omega)
\end{array} \]

Figure 1.3 Three layer metal-dielectric-metal SPP waveguide

Figure 1.3 represents the transverse cross-sectional view of an M-D-M type SPP guide with a dielectric slab of infinite width and finite thickness sandwiched between two metallic half spaces. This waveguide is also called a Gap Plasmon guide. The Gap Plasmon waveguides offer better modal confinement, less attenuation and are particularly suitable for coupling to dielectric waveguide due to continuity of the waveguide core [59]. Different variety of SPP guides under this category has been reviewed in [60, 61]. The dispersion relation and other modal features of D-M-D type SPP waveguide are further deliberated in chapter 2.

(d) Rectangular metal strip embedded in dielectric

\[ \begin{array}{c}
\epsilon_d \\
\epsilon_m(\omega) \\
\epsilon_d \\
\epsilon_d
\end{array} \]

Figure 1.4 2D SPP guide with a metallic stripe of finite width and thickness, embedded in uniform dielectric.
Figure 1.4 represents the cross-sectional view of a finite width rectangular metallic strip embedded in uniform dielectric. Bound SPP modes (both LRSPP and SRSPP) are supported in this structure with fields decaying exponentially away from all the interfaces and the corners in both dielectric and metal, thereby modal confinement is achieved in both the X and Y - directions [57]. As an alternative approach for making photonic circuits, long range SPP stripe waveguides have a unique feature – the possibility of using the same metal stripe circuitry for both guiding optical radiation and transmitting electrical signals that controls optical guidance. With the correct choice of the strip dimensions, only the LRSPP mode exists in such a structure with sufficient propagation length. However the modal guidance in metallic stripes is extremely sensitive to structural imperfections and therefore very critical from fabrication point of view. Similar wave-guiding properties are observed in nano wires when the cross-section of the metal rod is circular and stand as a promising candidate for optical interconnects in sub wavelength nano optic devices. An analytical technique for modal analysis of bound SPP modes supported by a rectangular metallic strip embedded in uniform dielectric is presented in chapter 5.

(e) Variable gap SPP guide

![Variable gap SPP guide diagram](image)

Figure 1.5 A variable gap SPP guide with a metallic ridge

A variable gap guide with a metallic ridge of finite width and height offers 2D confinement of SPP modes [57]. Since the Gap SPP effective index is strongly dependent on the gap width (increasing with its decrease) it is natural to exploit this dependence for achieving the 2D lateral mode confinement, e.g. by laterally varying the gap width as
shown in the figure. The G-SPP mode in such a configuration is laterally confined to a dielectric stripe between the closest metal surfaces, where the G-SPP effective index reaches its largest value. By increasing the refractive index of the material inside the gap the degree of localization of the guided SPP can be further improved.

(f) Channel SPP guides

Well confined bound SPP modes can be supported by suitably cut channels in metal slab and offer reasonably good propagation distance [57]. Channel Plasmon Polariton or CPP waveguides are of two types depending upon the shape of the nano sized channel cut in the real metal – (i) when the channel is a narrow rectangular groove in a metal, the supported CPP is referred to as Trench-CPP (figure 1.6), (ii) when the channel is a V-shaped groove in a metal, the supported CPP is called V-groove CPP (figure 1.7).

\[ \begin{array}{c}
\varepsilon_{d1} \\
\varepsilon_m(\omega) \\
\varepsilon_{d2} \\
\varepsilon_m(\omega) \\
\varepsilon_m(\omega) \\
\end{array} \]

Figure 1.6 SPP waveguide with a rectangular trench in metal

\[ \begin{array}{c}
\varepsilon_{d1} \\
\varepsilon_{d2} \\
\varepsilon_m(\omega) \\
\end{array} \]

Figure 1.7 SPP waveguide with V-shaped groove in metal
Trench CPP modes are strongly dependent of the geometrical parameters and the dielectric insert inside the trench. For deep trenches the modal features resemble to that of Gap Plasmon guides. Air-filled groove can be considered as two right-angled wedges hybridized by a finite-depth rectangular groove. The field is mainly confined at the two corners at the top of the trench and dielectric filling ($\epsilon_{d_2} > 1$) of the groove can be utilized for stronger confinement of field inside the trench. V-shaped groove is another variant in this class and are generally called Channel SPP guides. Here the geometry is very critical and the angle of the V-shaped groove has strong influence on modal characteristics. It is worth pointing out that CPP waveguiding in V-shaped grooves is counterintuitive. A certain groove depth (for a certain groove angle) is required to support a CPP mode. On the other hand, the CPP guiding approaches a cut-off and the CPP mode fields spill out of the groove when the groove angle increases. The choice of the groove angle is also subject to trade-off, as better CPP confinement achieved with narrower grooves would ensure smaller bend losses causing at the same time larger propagation losses.

We can consider a V-groove as a gap plasmon waveguide whose width continuously decreasing with increase of depth. Since light tends to remain confined in regions having higher refractive indices, sufficiently deep grooves support CPP modes that are confined to groove bottom, where the gap SPP effective index is maximum. Maximum localization of field strength near the bottom of the groove has various applications including nano focusing of light.

\( (g) \quad \textbf{Plasmonic slot waveguide} \)

\[
\begin{array}{c}
\hline
\text{Metal} & \hline
\end{array}
\]

\[
\begin{array}{c}
\hline
\text{Metal} & \hline
\end{array}
\]

\[
\begin{array}{c}
\epsilon_d \\
\hline
\end{array}
\]

\[
\begin{array}{c}
\epsilon_d \\
\hline
\end{array}
\]

**Figure 1.8** Cross-sectional view of 3D plasmonic slot waveguide geometry

For an asymmetric plasmonic slot waveguide, in which the surrounding dielectric media
above and below the metal film are different, the mode becomes leaky above a cutoff wavelength. For symmetric slots, over a wide wavelength range the modal fields are highly confined in the slot region and only slightly extend in the adjacent dielectric regions above and below the slot. Thus, the modal size is almost completely dominated by the near field of the slot. In addition, the size of the fundamental SPP mode is far smaller than the wavelength even when its dispersion relation approaches the light line of the surrounding dielectric media. This behavior is fundamentally different from that of conventional dielectric waveguides, in which the mode extends significantly into the low-index cladding, as the dispersion relation of the optical mode approaches the cladding light line. It is also fundamentally different from that of single-metal plasmonic waveguides (e.g. V-shaped grooves) in which a deep subwavelength mode is obtained only in a limited wavelength range, where the modal dispersion relation is far from the light line of the surrounding dielectric. Such a plasmonic slot waveguide could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices.

(h) **Dielectric loaded SPP waveguide (DLSPPW)**

![Dielectric loaded SPP waveguide](image)

**Figure 1.9 Cross-sectional view of DLSPPW structure**

The geometry of the transverse cross-section of DLSPPW is shown in figure 1.9. It is established that in contrast to the usual trade-off, the DLSPPW mode lateral confinement can be improved simultaneously with the increase in mode propagation length by choosing the appropriate ridge thickness [62]. In general, for each ridge thickness, the ridge width can be optimized with respect to the mode lateral confinement. In a theoretical analysis and simulation of another version of the dielectric loaded SPP
waveguide, a polymer ridge is deposited on a thin metal film of narrow width supported by a buffer dielectric layer covering a low index substrate [63]. It is theoretically predicted that such a configuration can offer propagation length of the order of 3 mm with lateral mode confinement of 1.6 μm at telecom wavelength of 1.55 μm.

(i) **SPP guide with periodic modulation on metallic surface**

![Diagram of SPP guide with periodic modulation](image)

Figure 1.10 Metallic grating structure on dielectric for SPP guidance

Routing of SPP on planar interface can also be achieved by locally modifying their dispersion characteristic via surface modulation. The surface modulation can be either in the metal side or in the dielectric and a periodic modulation thus leads to a grating structure which enables to add an extra in-phase wavevector component to the impinging light so that SPP mode is excited and sustained in the metal-dielectric interface.

1.3 **Basic schemes of excitation of SPP**

The excitation of surface plasmon modes is always an interesting and tricky problem. The basic waveguiding structure that supports a surface plasmon mode is a metal-dielectric interface. SPP, a surface electromagnetic wave has exponentially decaying field profile in both metal and the dielectric media with the maximum field strength right at the interface between two media (figure 1.11). The dispersion relation of SPP mode supported in a metal-dielectric interface is

\[
\beta = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m(\omega)}{\varepsilon_d + \varepsilon_m(\omega)}} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_d \varepsilon_m(\omega)}{\varepsilon_d + \varepsilon_m(\omega)}}
\]

(3)

c is the speed of light and the real part of \( \beta \) is the modal propagation constant and is also called the wave vector along Z axis, the direction of propagation. \( \frac{\beta}{k_0} \) is defined as the
effective index of the guided mode.

**Figure 1.11** SPP field profile in a metal-dielectric interface (Z is direction of propagation)

\[
h^2_{\text{d}} = (\beta^2 - k_0^2 \epsilon_d)
\]

**Figure 1.12** SPP dispersion diagram

The transverse component of the wave vector of the SPP mode in this case has components along Y direction only and their values in the dielectric and metal are:

\[
h^2_{\text{d}} = \beta^2 - k_0^2 \epsilon_d
\]
\[ h_m^2 = \beta^2 - k_0^2 \varepsilon_m \]  

The dispersion relation in equation (3) can be plotted as a \( \omega \) vs real part of \( \beta \) for real metals having dispersive complex permittivity \( \varepsilon_m(\omega) \) given by Drude's model in equation (1). The typical dispersion plot looks like figure 1.12, where the curve OA is dispersion plot of the SPP mode in a metal-dielectric interface derived from equation (3). The dispersion relation of free propagating wave in the dielectric is given by the following equation

\[ \omega = \frac{c}{\sqrt{\varepsilon_d}} \beta \]  

In figure 1.12, the line OB represents the plot of equation (6), also called the light line of dielectric. The dispersion curve shows that at low frequencies the surface mode lies close to the light line. As the frequency rises, the SPP curve moves away from the light line, gradually approaching an asymptotic limit, the surface plasmon resonant frequency \( \omega_{sp} \). This occurs at the frequency when the permittivity of the metal and dielectric are of same magnitude but opposite sign, producing a pole in the dispersion equation (3). The fact that light line in the dielectric always lies left to the SPP dispersion curve indicates that free propagating light can never interact with the SPP mode at the metal-dielectric interface and therefore excitation of SPP mode in a metal-dielectric interface by impinging free propagating light from the optically transparent dielectric side is not possible. It is also apparent that a freely propagating light wave can never have an evanescent type field profile that is necessary to match with requirement of SPP excitation in a metal-dielectric interface.

The two most important excitation schemes for surface plasmon modes at a single M-D interface are the Otto [64] and Kretschmann - Raether (K-R) [65] configurations. Both utilize total internal reflection (TIR) at the base of a prism to generate an evanescent field. While the former uses a thin air-gap (or dielectric), the latter uses a thin metal film as the buffer layer. The basic excitation scheme of Otto and K-R configuration are shown in figure 1.13 and figure 1.14 respectively.
The in-plane wavevector of the light in the prism base for an angle of incidence $\theta$ is expressed as

$$k_z = \beta = k_0 \sqrt{\epsilon_p} \sin \theta$$  \hspace{1cm} (7)

**Figure 1.13** SPP excitation in Otto configuration

**Figure 1.14** SPP excitation in K-R configuration
Where, $\varepsilon_p$ is the permittivity of the prism material. The straight line $OC$ represents the plot of equation (7) in figure 1.12. With suitable choice of angle $\theta$ and prism material ($\varepsilon_p$) at a particular frequency, one can adjust the slope of $OC$ so that it intersects the dispersion curve $OA$. At this condition we can write $\beta_{SPP} = k_0 \sqrt{\varepsilon_p} \sin \theta$. This phase matching condition results in excitation of SPP surface wave at metal-dielectric interface in both Otto and K-R configurations. The coupling scheme in both Otto and K-R configurations are also known as attenuated total internal reflection - therefore involves tunneling of the fields of excitation beam to the metal-dielectric interface where SPP excitation takes place.

The mismatch of the in-plane wavevector of the impinging photons and that of the intended SPP mode in metal-dielectric interface is the key issue to be addressed in SPP excitation problems. Besides the prism coupling schemes, another approach could be to excite the desired SPP mode through broadside evanescent tail coupling from a three layer dielectric waveguide as illustrated in figure 1.15.

![Dielectric Waveguide Diagram](image)

**Figure 1.15** SPP excitation using dielectric waveguide
The in-plane wavevector mismatch can also be overcome by patterning the metal surface with shallow grating of grooves or holes with a fixed spatial periodicity.

![Figure 1.16 Phase-matching of light to SPPs using a grating](image)

\( g = \frac{2\pi}{a} \) is the reciprocal vector of the grating and \( v \) is a positive integer.

### 1.4 Methods of analysis of SPP waveguides

In general the electromagnetic modal analysis of 1D SPP guides can be carried out exactly by solving Helmholtz wave equation with imposition of boundary conditions, but the analyses and computation become tedious particularly for the multilayer structures. The standard analytical techniques used for multilayer dielectric waveguides can be readily applied to 1-D SPP guides taking into account of the expected field profiles of the SPP modes in different regions of the guiding structure [66]. The 2D-guides in the domain of Plasmonics are more complicated and the exact electromagnetic modal analysis of such guides is not possible, in general. The basic 2D SPP waveguides are all open waveguide structures and the supported modes are hybrid in nature having all the six field components. The hybrid fields are solutions of the time harmonic vectorial wave equations
\[ \nabla \times \nabla \times E - \omega^2 \varepsilon(x,y)\mu E = 0 \quad (9) \]
\[ \nabla \times \varepsilon(x,y)^{-1}\nabla \times H - \omega^2 \mu H = 0 \quad (10) \]

The most commonly employed computational methods for studying the propagation characteristics in 1D and 2D-SPP guides are (1) Full-Vectorial Finite Difference Scheme [67, 68], (2) Method of Lines Technique [69] (3) Finite Element Method [70] and (4) Finite Difference Time Domain Technique [71]. To study 2D-SPP guides analytically, the Effective Index Method (EIM) is generally used [62, 72], which was primarily developed for solving the dielectric waveguide problems. But EIM, as an analytical technique when applied to 2D-SPP guides, appears to be an oversimplified modeling scheme because the principle of wave-guidance in SPP guides is altogether different from that in dielectric waveguides. Another analytical technique based on the Transverse Resonance Method (TRM) has also been used for analysis of surface plasmon modes in multilayer plasmonic waveguide structures [73].

Here we will discuss briefly about the basic principles of different methods generally used for theoretical analysis of 2D SPP waveguides.

(a) Full-Vectorial Finite Difference Scheme

It is a numerically stable and accurate finite difference scheme applied for vectorial analysis of dielectric and SPP waveguides. Generally homogeneous Helmholtz equations for the transverse magnetic fields are considered for finite difference discretization of the 1st and 2nd order partial derivatives within the computation mesh resulting from uneven discretization of the distances along the principal transverse axes (X, Y). By suitable choice of the mesh, all material interfaces are made to fall on the grid points. The size of the computation window is made large enough to ensure field values to be zero at its boundaries. The boundary and interface conditions in the guiding geometry are suitably incorporated and a characteristic equation for the waveguide is derived in the form \[ L[H] = \beta^2[H] \]. \( \beta \) is the complex propagation constant of the guided mode. The equation is solved for \( \beta \) and \([H]\) gives the magnitude of the transverse components of magnetic fields at all mesh points. Applying efficient iteration schemes, \( \beta \) and field profile of different propagating modes can be computed. This method has been applied in
both 1D and 2D SPP guides for modal analysis.

(b) Method of Lines (MOL)

MOL is suitable for 2D waveguides, uniform in the direction of propagation and its permittivity in the transverse plane can be expressed in terms of one transverse coordinate only, at least for different segments suitably drawn on the transverse geometry of the waveguide structure. MOL can handle complex and negative permittivity values without leading to any computational instability. Only one spatial dimension is considered to discretize the guiding wave equation along a set of parallel lines, called the gridlines. Incorporating interface conditions of field components of the guided electromagnetic waves to take care of layer to layer (segment to segment) media discontinuity, one can derive a homogeneous matrix equation of the form \([G][E] = [0]\). The complex propagation constant of different electromagnetic modes in the structure is evaluated by solving Determinant \([G] = 0\). Once the propagation constant of a mode is determined, the spatial distributions of all the six field components of the mode are generated. To restrict the size of the computation domain, perfectly matched layers with absorbing boundary conditions are suitably placed in the computation window so that desired eigen modes are least perturbed due to restricted size of computation window. Sometimes, depending upon the geometry of the problem we can use perfect magnetic/electric walls to restrict the computation window taking proper care that no undue reflection takes place from such boundaries. Since all the spatial dimensions are not discretized in MOL technique, it is expected to offer better results when compared with other numerical techniques and it is often called as a semi analytical technique.

(c) Finite Element Method (FEM)

The FEM is one of the most versatile, powerful, and successful numerical methods for many branches of engineering, including the characterization of many structural, thermal, and fluid dynamics problems. FEM is a technique for numerical solution of partial differential equations or integral equations. In this method, the geometrical domain of a problem is suitably divided into a finite number of sub-regions (usually triangles), called "elements" and the partial differential equation is replaced with a corresponding
Functional. Subsequently, a variational method is used to minimize the functional in order to obtain variational features in the algorithm and the field distribution in the transverse plane is obtained. Each of the elements can have different shapes and sizes, and by using many such elements, a complex problem can be accurately represented. This type of analysis has also been established as one of the most powerful and accurate methods for very high-frequency optical waveguides and guided-wave photonic devices. A wide range of guided wave devices can be modeled as each element can also have different material parameters, such as permittivity with real and complex terms, could be anisotropic tensor in nature, and have material nonlinearity and loss or gain factors. Finite-element approach based on a full-vectorial H-field formulation, in conjunction with the perturbation technique, has been used to study SPP modes in a few guiding structures.

(d) Finite Difference Time Domain Technique (FDTD)

FDTD technique has been used for analysis of SPP waveguides extensively. The main advantage of FDTD is its ability to model complicated 3D guides and to provide the temporal snap-shots of the electromagnetic fields supported in the waveguide. It is an efficient numerical technique to solve Maxwell’s equations. In FDTD technique, the structure is split into small volumes called the Yee cells and the electromagnetic field components are computed at half space and half time intervals using discretized Maxwell’s equations [71]. Computations over a large number of time intervals simulate a steady state evolution of the eigen modes. The time and space derivatives of the field functions are discretized using appropriate finite difference formulae. The space and time intervals are carefully chosen to avoid any numerical instability and spatial resolution problems. Original FDTD technique could not be applied to real metals having negative permittivity because of numerical instability. However modern FDTD techniques [74, 75] can accommodate real metals at optical frequencies in the wave guiding structure appropriately and the method is successfully applied to SPP waveguide problems.

(e) Effective Index Method (EIM)

The effective index method is often applied for analytically solving the modes for 2D
SPP waveguides [62, 72, 76] as an alternative to computationally intensive numerical techniques. The method is particularly suitable for waveguides having rectangular geometries and for the linearly polarized modes far from cutoff. Generally the EIM analysis is carried out in two consecutive steps where in each step the dispersion equations of 1D waveguides are used. To elaborate the concept further let us consider the DLSPPW guide shown in figure 1.9. The first step in EIM approach would be to calculate the effective index $N_{\text{eff}}^*$ of the guided modes in planar four-layer waveguide structure in figure 1.17 derived from figure 1.9 by making the width of the polymer layer infinite. Each of the four layers is considered of infinite lateral extension in the X direction. The top (air) and bottom (dielectric) layers are considered to be semi-infinite in depth in the Y direction.

![Figure 1.17](image)

Figure 1.17 The four-layer structure considered in the first step of EIM

In the second step of EIM, the polymer width is being reduced from infinite width to the width of the polymer ridge in the actual waveguide structure in figure 1.9 and $N_{\text{eff}}^*$ is used for calculation of the final mode effective index $N_{\text{eff}}$ by considering the equivalent three-layer structure with vertical interfaces as shown in figure 1.18.

![Figure 1.18](image)

Figure 1.18 The three-layer structure considered in the second step of EIM

The SPP modes in the structure are bound to the metal-polymer interface, the effective
index of a SPP propagating along the metal-air interface \( n_{SPP} \) is used outside the ridge sub region for calculation of \( N_{eff} \). The EIM calculation can be carried out following a different approach in reducing the 2D geometry to two 1D waveguide structures which are to be dealt with consecutively.

Figure 1.19 The three-layer structure considered in the first step of EIM in the alternative approach.

Figure 1.20 The four-layer structure considered in the second and final step of EIM in the alternative approach.

In the alternative approach, first an infinitely tall polymer ridge is considered as in figure 1.19 and the three-layer air-polymer-air structure with infinitely long vertical interfaces (polymer layer thickness is same as the width of the polymer ridge in original structure in figure 1.9) is analyzed. In this step the effective index \( N_{eff}^* \) can be calculated as a function of the polymer ridge width and computed \( N_{eff}^* \) is then used to compute the \( N_{eff} \) of the four layer structure shown in figure 1.20, which gives the final effective index of the DLSPPW guide. The thickness of the layer having effective index \( N_{eff}^* \) in figure 1.20 is identical to the original thickness of the polymer ridge in figure 1.9. In either approach
of ELM, the polarization of the dominant field component of the original waveguide is taken into consideration while solving the 1D multilayer waveguides for TE/TM modes as per necessity.

(f) **Transverse Resonance Method (TRM)**

Transverse Resonance Method (TRM) is based on circuit representation of electromagnetic waveguides and the method has been extensively applied for analysis of closed metallic waveguides and multilayer dielectric waveguides. The technique has also been applied to the studies of surface plasmon modes in three layer plasmonic structures [73]. If the waveguide structure is uniform in X direction and having its propagation along Z direction, then a transverse resonance condition can be applied at any point in the Y direction by considering equivalent transmission lines for different layers in the waveguide structure cascaded along Y axis. Generally the transverse resonance condition is represented in terms of transmission line impedances as \( \frac{1}{Z(y)} + \frac{1}{Z(y)} = 0 \) which implies \( Z(y) + Z(y) = 0 \). The condition can be applied at any point \( Y = y \) in a multilayer structure and it is said to be a resonant condition because it essentially indicates that a finite response is possible from zero excitation and the transverse field distribution in such a structure is sustainable. The impedances \( Z(y) \) and \( Z(y) \) are the input impedances of transmission lines in the transverse direction (Y-direction) when looked vertically up and down respectively at the point \( Y = y \). By strategic choice of \( Y = y \) point and taking care of the symmetry (if the waveguide geometry so permits), the application of transverse resonance condition readily gives the dispersion equation of the waveguide. This method is particularly suitable for multilayer structure when compared to standard field matching technique where one needs to incorporate the detailed interface conditions at each layer to layer discontinuity. TRM gives a better understanding of waveguide structures from circuit point of view and it is possible to understand certain features of the waveguide (e.g. condition of cutoff) using the circuital representation of the waveguides. However this method has yet not been developed for the analysis of practical 2D plasmonic waveguides where the transverse fields are function of both X and Y coordinates.
In the present research work, the problems of excitation of SPP in 1D planar structure have been addressed through analytic and numerical techniques (MOL). Though there are several numerical simulation techniques available, we thought that exploring the possibilities of solving 2D-SPP guides by developing some approximate but more rigorous analytical technique would be definitely a very important research area in field of Plasmonics and Nano-Optics. This is particularly important because all the 2D SPP waveguides are open structures and the modal solutions in a closed form are not possible. In the present research work, an approximate analytical technique particularly suitable for 2D rectangular geometry SPP guides has been developed and the same is applied successfully to a few plasmonic structures namely metallic nano wires, nano hole in real metal and rectangular trench of sub-λ dimension cut in real metal (chapter 5 and chapter 6). In the proposed method which we call a Full Hybrid Trial Field method, the transverse cross section of a uniform (in the direction of propagation) SPP waveguide is considered and segmented into homogeneous regions. We then intend to write the trial solutions of the vectorial wave equation (9) and (10) in each region. But writing a trial solution (by inspection) for complicated vector differential equations (9) and (10) is not possible in general. However the total fields (E and H: All the six field components) can be expressed as superposition of suitable pair of partial mode fields: for example partial modes, \( TE^X (E_x = 0: TE \to -X) \) and \( TM^X (H_x = 0: TM \to -X) \) can be considered for a structure to construct the total fields. The fields of the partial modes satisfy Helmholtz wave equations \( \nabla^2 \psi^{TE} + [\omega^2 \epsilon(x,y) - \beta^2 \psi^{TE}] = 0 \) and \( \nabla^2 \psi^{TM} + [\omega^2 \epsilon(x,y) - \beta^2 \psi^{TM}] = 0 \), where \( \psi^{TE} \) and \( \psi^{TM} \) represent the TE, TM partial mode fields, \( \beta \) is the complex propagation constant, \( \epsilon(x,y) \) is the permittivity function in the transverse plane and \( \mu \) is the permeability and is taken as permeability of the free space \( \mu_0 \) for non magnetic media. The total field in the guided wave structure can be expressed as \( \psi = f(\psi^{TM}, \psi^{TE}) \), as a superposition of \( \psi^{TE} \) and \( \psi^{TM} \). In many guided wave geometries we can write the trial solutions for the partial fields on inspection, at least for the segmented homogeneous regions in a segment-wise continuous manner. In the next step the total fields are derived from the partial fields. Now applying field matching techniques, we can derive a set of transcendental equations that can be solved for the
modal eigen values, which are complex numbers.

1.5 Organization of the thesis

The dissertation consists of seven chapters including this introductory chapter. The contents of the remaining chapters are described below in a summarized manner.

The Chapter 2 covers the basic planar guides using dielectric-metal interfaces for guiding surface plasmon waves. It has already been discussed in this introductory chapter that the surface plasmon polaritons are transverse magnetic (TM) polarized optical surface waves that propagate, typically, along an interface between a real metal and dielectric with fields having their maxima at the interface and decaying exponentially away into both the media. A single interface between a metal half space and a dielectric half space acts as the basic guiding structure for SPP. A dielectric-metal-dielectric or metal-dielectric-metal types structures can also support SPP modes with some interesting features. The three layer double interface structures can be thought of as a coupled structure of two single interface waveguides. The electromagnetic analysis and modal characteristic properties of single interface Dielectric-Metal (D-M) guide and double interface (D-M-D and M-D-M) guides are briefly presented as a foundation work for the remaining chapters of the thesis. The concepts and characteristics of Long/Short Range Surface Plasmon Polariton (LRSPP/SRSPP) modes are also introduced in this chapter.

In Chapter 3, the calculation of modified wave-vector of surface plasmon modes in presence of auxiliary three layer dielectric waveguide is presented. Surface Electromagnetic Waves (SEW) that exist at an interface between two media having opposite signs in the real parts of their permittivity [77] have been known for many years. The propagation characteristics of surface plasmon modes in a single metal-dielectric interface can be calculated using continuity of the electromagnetic fields. Only TM type SPP mode is supported by such an interface having only three field components with exponential decay on either side of the interface in transverse direction [78]. Another important outcome of the analysis of a single M-D interface is that no free electromagnetic wave while impinging upon the interface can excite a SPP mode [9]. This has already been discussed in section 1.3. Otto configuration and Kretschmann-
Raether (K-R) configuration are the two generally used schemes for excitation of SPP in a single M-D interface by light. Improvement in single-interface propagation characteristics can be achieved in a three-layer structure, having a core of metal layer of finite thickness and infinite width sandwiched between two semi-infinite dielectric layers [79]. As in the case of single M-D interface, the SPP cannot be excited in upper or lower M-D interface of a three layer D-M-D structure by a free propagating wave. However in all the analyses of a single interface or a three layer double interface SPP wave-guiding structure, only isolated structures are considered ignoring the presence of coupling waveguide component (or prism) necessary for generation of an evanescent tail in the buffer layer. Efficient SPP mode launching scheme that can be conveniently integrated is important for Photonic Integrated Circuits (PIC) and as such has been receiving attention in recent years [80, 81]. In this chapter of the thesis we have examined the excitation of SPP modes in (a) single M-D interface and (b) three-layer double interface D-M-D, in the presence of a vertically coupled parallel three layer dielectric slab waveguide. Excitation of SPP modes at metal-dielectric single interface and dielectric-metal-dielectric double interface from a vertically coupled three-layer dielectric guide has been analytically modeled as four-layer and five-layer structures, respectively. Eigenvalue equations are derived and solved to obtain plasmonic modes as well as perturbed dielectric waveguide mode in the auxiliary coupling waveguide. The role of buffer layer thickness in a composite 1D waveguide structure becomes apparent for proper excitation of SPP modes [82, 83].

In Chapter 4, the Method of Lines (MoL) computation of surface plasmon modes on metal – dielectric interface in Otto and Kreshmann-Raether configurations is presented. The work presented in this chapter is a continuation of the work covered in chapter 3. The dispersion of propagation constants of Surface Plasmon Polariton modes at a metal-dielectric interface with the thickness of buffer layer in both the Otto and the Kreshmann-Raether configurations has been modeled using Method of Lines [84]. The precise computation of $\beta$ for a finite buffer layer thickness and its dispersion with the buffer layer thickness are important to study particularly for the quality and nature of the surface plasmon mode being excited at the metal-dielectric interface. Perfectly Matched
Layer (PML) Absorbing Boundary Condition (ABC) is applied to restrict the size of the MoL computation space for computing the dispersion of plasmonic $\beta$ for different values of buffer layer thickness [85]. The model has been validated by comparing with the published results obtained by approximate theoretical formulae for modified Otto configuration with multi-layered dielectric buffer [86]. In both the Otto and K-R excitation schemes, the SPP mode is inherently leaky, but with suitable adjustment of the buffer layer thickness we can realize quasi-bound plasmon mode in the metal-dielectric interface. To see how the surface plasmon mode in prism coupling configurations evolves as the buffer thickness is varied; the normalized eigenvector is plotted for several buffer layer thicknesses. In both Otto and K-R configurations, the SPP mode becomes lossy (leaky) for very thin buffer thicknesses because of enhanced coupling of the surface wave with the free electromagnetic wave inside the prism. This effect is also called loading of SPP mode by the prism [87].

In Chapter 5, an analytic method is presented to study the bound plasmon polariton modes guided by a metallic wire of rectangular cross section embedded in uniform and homogeneous dielectric medium. As mentioned in section 1.4, one of the main objectives of the thesis was to develop some independent analytical technique to study the propagation characteristics of two dimensional SPP waveguides.

The studies on SPP modes supported by metallic wire of rectangular cross section embedded in dielectric is important particularly for designing sub-wavelength optical components and interconnects. Being an open structure, the supported modes in such a stripe waveguide would be hybrid in nature with all the six electromagnetic field components. Like the case of a rectangular dielectric waveguide, the exact analytical modal solution for a metallic strip is not possible. Modal analysis of a stripe geometry SPP waveguide is an active area of research and significant contributions have been made using semi-analytical MoL technique [88, 89] by Berini and using a full-vectorial finite difference scheme [68] by Al-Bader. Numerical methods and simulation techniques work on the principle of solving the complex electromagnetic wave problems using the schemes of discretization in space and time domain, depending upon the technique used, and imposition of spatial interface conditions numerically. A good review on numerical
simulation of long-range surface plasmon polariton (LRSPP) may be found in [90]. Such numerical simulations yield the graphical modal field profiles and other propagation characteristics very efficiently but if someone is interested in an approximate expression for electromagnetic fields in such a waveguides, there is no answer to that. Approximate expressions may become useful, for example, in some specific studies where one intends to apply a variational technique. Together with different simulation techniques, the traditional effective index method (EIM), generally used in dielectric waveguide problems, has also been utilized in modeling SP waveguide components [72, 75]. EIM is simple but its applicability to the rectangular SP guide problem appears to be limited to approximate results.

In this chapter we have computed the propagation characteristics of bound SP modes supported by a rectangular metallic strip embedded in uniform dielectric at optical frequency using suitable full-hybrid trial field functions and checked the validity of the trial fields by comparing the results of computation with published data. In this approach, we have constructed the prospective trial transverse spatial functions for $E_y^{TE}$ and $H_y^{TM}$ fields corresponding to $TE_x^x (E_x = 0)$ and $TM_x^x (H_x = 0)$ modes, respectively, and derived all the six field components of the hybrid plasmon modes of the structure from superposition of $TE_x^x$ and $TM_x^x$ mode families [88]. Applying necessary boundary conditions, the eigenvalue equations are derived and solved for effective index of different fundamental modes with different symmetry considerations. The results of computation with the trial field modeling are presented in this chapter and are found to be in good agreement with the data presented by Al-Bader [68] and Rashid Zia et al [91]. It is observed that the degree of agreement of results using present technique with that of Berini in [88] is better in case of thin stripe. In trial field modeling of the strip guide, the modal solutions are assumed to be of separable variable type. However, in case of a plasmon guide of rectangular cross-section, the coupling of fields between two adjacent perpendicular edges via the corner may be significant and is likely to have appreciable influence in modal solutions [88, 89]. In X-Y coordinate system such a coupling cannot be accommodated in the formulation. The contribution of the corner regions can be taken into consideration in two ways for possible improvement in results. One would be to
apply variational method [92] and use the trial field solutions. The other would be to solve the problem in a cylindrical coordinate system [93, 94].

The fully-hybrid trial field formulation that has been presented in this chapter is also applied to a subwavelength rectangular hole in real metal. Transmission of optical signal through subwavelength holes in real metal has become a subject of interest recently. Noble metals like gold, silver or copper exhibit wavelength dependent optical constants [3]. It has been discovered that there is plasmon assisted Extra Ordinary Transmission (EOT) of light through subwavelength holes perforated in opaque metal films [95]. Since the experimental finding of EOT, a number of theoretical investigations have been carried out by the researchers to understand the phenomenon. One interesting investigation on this problem, by R. Gordon and his group, predicts enhancement of cut-off wavelength of the rectangular hole with decreasing hole-size [96]. If the metal is perfect electric conductor (PEC), the transmission characteristics of electromagnetic energy through such a hole can be considered as that in a rectangular waveguide (RW). Among the all possible modes in a RW, the $\text{TE}_{10}$ mode is the lowest one having cut-off wavelength at $\lambda_c = 2 \times 2w = 4w$ ($w=$ half of the larger dimension of the rectangular waveguide), implying that there would be no propagation at $\lambda > \lambda_c$. However this is not true in case of a real metal and the plasmon assisted transmission makes propagation possible beyond $\lambda_c$ calculated from RW theory.

To study the propagation characteristics through a rectangular hole in real metal we have applied the same formulation proposed in this chapter to test the applicability of the trial function technique in a complementary problem. The data obtained from the trial field method are in very good agreement with the results published in [96], computed by EIM and numerical simulations.

In Chapter 6, the analytic modeling using full-hybrid trial-field functions has been applied to determine the propagation characteristics of trench waveguides for channel plasmon-polariton. Apart from the basic SPP guiding structure of metal strip embedded in homogeneous or inhomogeneous dielectrics and its variants, Gap-SPP and Channel-SPP have been shown to have several desirable features [97, 98, 99, 100]. Channel SPPs, commonly referred to as Channel Plasmon Polariton or CPP, are guided
by two basic structures. (a) The channel is a V-shaped groove in a metal. The supported CPP is generally referred to as V-groove Channel Plasmon Polariton or V-groove CPP. (b) The channel is a narrow rectangular groove in a metal. The supported CPP is referred to as Trench Channel Plasmon Polariton or Trench-CPP. Simultaneous availability of subwavelength lateral confinement and relatively long propagation length is the most desirable feature of CPP. Photonic components based on both types of CPPs have been demonstrated in practice [101, 102, 103]. Together with different simulation techniques, the effective index method (EIM), traditionally employed in dielectric waveguide problems, has been used for determining the propagation characteristics of channel-SPP guides and in modeling SP waveguide components [101, 102]. The main attractive feature of EIM is that the characteristics of 2D guides can be predicted by combining results obtained from analysis of 1D guides. Another method, the semi-analytic Method of Lines, has proved to be a very useful tool for numerical modeling of plasmonic waveguides [84, 88, 89, 104]. Minh and others [105] recently have applied MoL to calculate the propagation characteristics of Trench-CPP waveguides and have compared their results with those obtained by EIM [72] and FDTD [106].

In this chapter of the thesis, an analytic modeling of Trench-CPP guides using full hybrid trial field functions has been presented. The computed values of complex effective index and propagation length for different trench dimensions, different dielectric inserts in the trench and at different wavelengths of operation are computed and compared with those in [72, 105]. The literature on Trench-CPP is very much limited at this time. The reported comparison of EIM and MoL results showed only partial agreement [72, 105]. Our results, obtained with trial-field modeling, agree well in parts with EIM and partly with MoL data. The problem of discrepancy appears mainly in the imaginary part of the effective index or the propagation length, particularly for small values of trench depth. As such any claim about one particular method being more accurate than the others may not be justified at this point of time. Perhaps more detailed study with more rigorous formulation will resolve this issue.

In Chapter 7, a summary of the work and the conclusion is presented. The work covered in the thesis has mainly dealt with guidance of SPP waves in both one and two
dimensions. In case of 1D-SPP guides, the importance of accommodating the presence of auxiliary optical waveguide or prism while calculating the SPP wave-vector for D-M or D-M-D structures has been emphasized. As such no free electromagnetic wave can excite SPP waves in an isolated D-M, D-M-D or its complementary M-D-M structure. Therefore it appeared to be interesting and useful to investigate how the SPP wave-vectors in such simple 1D guides get modified in presence of the auxiliary guides, necessary for SPP excitation through the evanescent tail across the so called “buffer layer”. The study revealed that the thickness of buffer layer has a very critical role in SPP excitation in nano-optical guides and an accurate theoretical calculation scheme can help in designing the appropriate buffer layer thickness so that the excited SPP mode is not loaded and remains at least quasi bound (if not a truly bound mode) to the interface.

In the present thesis, an important analytical technique based on full-hybrid trial field functions has been proposed [107, 108]. The propagation characteristics of three different 2D SPP guiding structures namely (1) the rectangular metal stripe embedded in uniform dielectric, (2) rectangular nano-hole in real metal and (3) rectangular trench in real metal have been analyzed using the technique and results are found to be in good agreement, when compared with the data obtained by other numerical techniques. The method proposed in the thesis is simple but fairly accurate and particularly suitable for rectangular geometries. For the sake of completeness, the dissertation will end with several Appendices covering the (1) Important derivations used in the trial field formulation, (2) Complex root finding techniques and (3) Techniques used for solving simultaneous equations yielding complex roots.

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