Chapter 7

Summary and scope for future studies
The work covered in this thesis has mainly dealt with the guidance of Surface Plasmon Polariton (SPP) waves in both one and two dimensions.

One of the most fundamental and interesting features of SPP wave is the fact that it cannot be excited in a metal – dielectric interface by impinging free electromagnetic wave from either side of the interface. 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. It therefore appeared to be interesting and useful to investigate how the SPP wave-vectors (dispersion relations) in such simple 1D guides get modified in presence of the auxiliary guides, necessary for SPP excitation through an evanescent tail across the so called “buffer layer”. We first applied the conventional trial solution approach by modeling the wave guides as multilayer structures and subsequently the semi analytical Method of Lines (MOL) technique was used for computation of surface plasmon modes on the metal – dielectric interface in Otto and Kreshmann - Raether configurations to study the dispersion of propagation constants of SPP modes at a metal-dielectric interface with the thickness of buffer layer in both the configurations. The precise computation of propagation constant 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. The studies 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 quasi bound to the interface. It is also found that the SPP wave-vectors in a M-D or a D-M-D interface when excited from a vertically coupled planar dielectric waveguide or prism do not suffer significant perturbation as long as the SPP modes are excited in these interfaces and therefore it can be concluded that in case of SPP excitations in M-D, D-M-D or multilayer structures we can safely treat the isolated structures without considering the presence of auxiliary exciting waveguides to derive the SPP dispersion relations. But the role of buffer layer thickness is very important to ensure bound mode excitation in the metal-dielectric interfaces. We could get an estimation of “too large” or “too small” buffer layer thicknesses which can

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be of immense help in actual design problems. The loading of SPP modes in presence of
the auxiliary waveguide or prism is another important aspect and our study using MOL
technique could graphically address the loading issue in case of prism configurations.

Though the shape of the prism in case of prism configurations is not important as
long as the total internal reflection takes place at the prism base, the parallelism of the
prism base with the plane of metal-dielectric interface is very important and the effect of
deviation from the perfect parallelism can be a good area of future research and may find
useful applications in nano sensor technologies.

In the thesis, an important analytical technique based on full-hybrid trial field
functions has been proposed. The propagation characteristics of three different 2D SPP
guides namely (1) the rectangular metal stripe embedded in uniform dielectric, (2)
rectangular nano hole in real metal and (3) rectangular nano 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. In this approach, we
have constructed the prospective trial transverse spatial functions for $E_y^{\text{TE}}$ and $H_y^{\text{TM}}$
fields corresponding to TE$^x$ ($E_x = 0$) and TM$^x$ ($H_x = 0$) modes, respectively, and derived
all six field components of the hybrid plasmon modes of the structures from
superposition of TE$^x$ and TM$^x$ mode families. Applying necessary and suitable boundary
conditions, the eigenvalue equations are derived and solved for effective index of
different fundamental modes with different symmetry considerations. The method
proposed in the thesis is simple but fairly accurate and particularly suitable for
rectangular geometries. It is well known that the dispersion relations in closed forms
cannot be derived for such 2D SPP waveguides and several numerical and semi analytical
techniques are still tried to tackle this kind of waveguide problems. Most widely used
techniques are of course (a) Method of Lines and (b) Effective Index Method. The
success of the technique proposed in this thesis relies not only on the right construction
of the trial field functions but also on the most prudent choice of the boundary conditions
that can lead to derivation of useful dispersion relations.

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The classification of bound SPP modes in rectangular metallic stripe embedded in uniform dielectric has been discussed considering modal symmetries along the principal axes in the waveguide geometry. The dispersion characteristics of the propagation parameters for all the fundamental bound modes ($sa^0$, $aa^0$, $ss^0$ and $as^0$ modes) supported in metallic stripe have been studied using our technique of full hybrid trial field formulation. The bound Plasmon modes in general have interesting characteristics of increased attenuation with better transverse confinement. Long Range SPP (LRSPP) modes are of practical interest which may offer longer propagation length with reasonable transverse confinement. The proposed trial field modeling may be successfully applied to a wide range of stripe geometries without any need of computation intensive simulation tools. The same set of dispersion equations derived using the technique may be further used to compute the higher order SPP modes in the rectangular stripe geometries.

A rectangular nano hole cut in a real metal can be considered as a complementary problem of a nano metallic stripe and we have applied full hybrid trial field formulation in studying the features of SPP assisted mode propagation (fundamental TE$_{10}$ mode) in nano holes.

The rectangular nano trenches cut in real metal is emerging as a basic SPP guiding structure which offers simultaneously good modal confinement and improved propagation distance. The application of full hybrid trial field modeling to study the fundamental SPP mode in trench waveguides has yielded interesting results and has prospects for applications in practical design problems where SPP propagation at different wavelengths and with different dielectric inserts in the trench are important to investigate.

Three basic 2D guiding structures have been discussed in the thesis using full hybrid trial field modeling. In photonic integrated circuits coupled structures are very important for various applications and the method proposed in the thesis may prove to be very a useful tool in studying the SPP modes supported in structures like coupled stripes or coupled trenches.
In our work we have used x-y coordinate system matching with the principal transverse directions of the waveguides. It would be interesting to tackle the problems in cylindrical polar coordinate systems also. Approximate modal analysis of rectangular optical waveguide geometries using cylindrical polar coordinates have been tried already [1, 2]. But the treatment would not be analogous in SPP waveguides because the guiding differential equations would be different in form involving modified Bessel functions of first and second kind in the trial solutions. The formulation in polar coordinate will inherently couple the independent modes supported in two mutually perpendicular M-D interfaces and the analysis would yield better hybridization of the edge modes. It is therefore believed that the accuracy of mode computation can be improved if one can solve the problem in cylindrical coordinate system. Among the already reported techniques, Goell’s method [1] heavily depends on the selection of points on the interfaces at which the field matching conditions are actually imposed. An extensive research is necessary to design a suitable algorithm to select the set of points on the boundaries for the purpose of field matching. On the other hand, Brand’s method does not require field matching at any specific points on the boundaries; rather it takes advantage of Fourier expansion to derive the dispersion relations. Applying such technique for SPP guides of rectangular geometries would be difficult since the modified Bessel functions involved in the analyses are of monotonically increasing or decreasing nature.

References
