Novel optical devices based on surface wave excitation at conducting interfaces

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Abstract
In this paper, the excitation of surface waves in the presence of interface charges is discussed. Interface charges affect the dispersion of surface waves, and therefore they can be used in various applications such as optical modulators, switches, sensors and filters. These waves can be superior to surface plasmon waves since they are not lossy. The lossless property is satisfied in a limited range of millimetre waves to far infrared.

1. Introduction

Regarding the rapid growth of fibre optic and optical communication, there is a high demand for faster and smaller optical devices. Fortunately, advances in semiconductor growth techniques such as molecular beam epitaxy (MBE) have enabled the possibility of fabrication of high quality films, together in the precise monolayer compositional control [1]. This makes new classes of devices accessible, which are based on wavelike behaviour of electrons [2–4], guided-wave optical devices or a group of devices that are based on interaction between electromagnetic fields and electric charge layers.

The proposed devices based on the interaction of electric charge and electromagnetic field wave usually use the excitation of surface plasma waves in metal–dielectric interface [5–8], light induced plasma layers inside semiconductor materials [9] or interaction of electromagnetic wave and depletion layer such as far-infrared light modulator and switch proposed and developed in 400 kHz range by Kuijk, Vounckx, Stiens and Borghs [10–12]. They have used the concept of reflection of light from a depletion layer that acts as a mirror for light frequencies below the layer’s plasma frequency. However, fast modulation had not been achieved because of the slow dynamics of the designed device. In this class of devices, Jung et al [13] investigated integrated optics waveguide modulator based on surface plasmon resonance which is theoretically capable of switching speeds in the gigahertz range, but it is limited to TM polarized waves, and is lossy. Liu et al [14] proposed an optical switch using light induced plasma layer. They have used the impact of optically controlled plasma layer on the propagation and attenuation constants. Their structure is also lossy.

The possibility of fast guided light modulation and switching in dielectric slab waveguides with a very high switching speed has been recently studied [15, 16]. The corresponding device is based on the interaction of interface free charge layers and the incident light beam, the density of interface free charge layer being controlled by a transverse dc voltage. This device is also proposed for applications such as optical storage and optical transistor [17], as well as programmable diffractive elements [18]. Recently, by solution of Maxwell equations subject to non-homogeneous boundary conditions, a full theoretical analysis of this device with the assumption that the thickness of the interface charge layer is much smaller than the wavelength has been presented [19]. This device is expected to be capable of working in the far infrared up to infrared region. In this paper, interface conductivity is used in order to excite surface electromagnetic wave. Interface charges affect the dispersion of surface waves, thus, they can be used for exciting them. It has been shown that layered structures in the presence of interface conductivity can support surface electromagnetic waves for both major polarizations. This property is utilized and several novel devices are proposed. The devices based on such structures can be lossless since conductivity can have a vanishing real part in a limited frequency range [19].

This paper is arranged as follows: in section 2, surface electromagnetic wave (SEW) in the dielectric–dielectric interface in the presence of interface conductivity is studied for TM and TE polarized modes, and the corresponding dispersion equation is derived. In section 3, the dispersion equations of SEW on multilayer structures for both TM and TE polarized waves are discussed. Also, an efficient algorithm for deriving the dispersion equation of SEW in multilayer structures in the presence of interface conductivity is proposed. The analytical expression of dispersion equation for some special cases is also derived. In section 4, numerical
correspondingly, the dimension of outward normal, and the z-axis is presented. Finally, conclusions are made in section 5.

2. SEW in the dielectric–dielectric interface

In this section, the surface electromagnetic wave propagation in the dielectric–dielectric interface is studied by direct solution of Maxwell’s equations and applying proper boundary conditions. The arrangement of two adjacent dielectric semi-infinite slabs is illustrated in figure 1. Here, the y-axis is outward normal, and the z = 0 or x–y plane is equivalent to the interface of medium 1 in the z < 0 region and medium 2 in the z > 0 region. It is supposed that the wave propagates along the positive direction of z-axis so that the y-component of the wave vector is zero. The interface of the two media in contact has an interface conductivity denoted \( \sigma \) that is different and cannot be neglected. The effective mass of the holes is used in place of \( m \) in the order of 100 Å. If the free interface charge is negative, \( \sigma \) is the wave number in free space. It is easy to show that this dispersion equation is only satisfied with \( \text{Im} [\sigma] > 0 \), or \( \alpha < 0 \), where \( \alpha = -j/\kappa_0 \). At frequencies of interest, the surface conductivity given by

\[
\sigma = -j\omega \varepsilon_n e^2/m^*\omega = -j\omega \varepsilon|q_1|/m^*\omega
\]

is purely imaginary [20]. Here \( \varepsilon \) is the carrier (electron or hole) charge, \( n, q \) are the surface number and charge density, respectively, \( m^* \) is the effective mass of electrons or holes, and \( \omega \) is the angular frequency of light. It is to be noted that the complex conductivity \( \sigma \) can be regarded as a net change in the local permittivity being equal to \( -j/\kappa_0/d \), where \( d \) is the effective thickness of the charge sheet, typically in the order of 100 Å. If the free interface charge is negative, the effective mass of the electrons is used in place of \( m^* \), otherwise the effective mass of the holes is used. \( f \) is a factor between –1 and +1, which determines the overall effect of the accumulated charge density. The magnitude and polarity of \( f \) are important, and its meaning is explained below.

The interface charge of two dielectrics is generally composed of three major parts [21, 22]:

1. The depletion layer, which results from the initial imbalance between the Fermi levels of the adjacent dielectrics.
2. Trapped electrons or holes in the quantum wells across the valence and conduction bands, which may be formed due to a difference in the band gaps (just like the two-dimensional electron/hole gas in heterostructures and HEMT).
3. The trapped charge in the interface traps formed by lattice imperfections and the interface energy states, which reside in the forbidden energy gap.

The effect of interface traps and interface states can be made negligible, especially for well-fabricated devices, by precisely controlled processes such as MBE. However, the contributions of depletion layer and quantum well trapped charges to the interface conductivity are different and cannot be neglected.
The depletion layer charge is formed by the ionized impurities, which are immobile. Therefore, its contribution to the interface conductivity (6) should be described by a positive sign, resulting in a net increase in local permittivity. On the other hand, trapped charges in quantum wells are mobile (in parallel to the interface) and enjoy a much smaller effective mass; therefore, their contribution should be described by a negative sign, resulting in a net reduction of the local permittivity. Generally speaking, as long as heterostructures are not considered, there would be no quantum well trapped charges, and only the depletion layer contribution would be enough to consider, and in such a case \( f \) would be equal to +1. Otherwise, a detailed and complicated numerical study of the interface charges would be necessary, and \( f \) will no longer be equal to unity; in that case the overall effect of depletion and quantum well charges would result in \( f \approx -1 \). Further explanation about how a net surface charge can be produced across the dielectric interface can be found in [19, 23].

Also, it is simple to check that the above results show that there is no surface electromagnetic wave in the absence of the charge layer with \( \sigma = 0 \). Thus, the presence of interface current \( J_s \) has enabled SEW propagation in the dielectric–dielectric interface.

### 2.2. TM polarized light

The same process can be repeated for TM polarized waves. For TM polarization, electromagnetic fields for \( x > 0 \) are

\[
H_{j2} = H_{j20} \exp[-j\omega x] \exp[j(\omega t - \beta z)],
\]

\[
h_2 = \sqrt{\beta^2 - k_0^2 n_2^2},
\]

\[
E_{z2} = \frac{jh_2}{\omega \sigma_0 n_2^2} H_{j20} \exp[-j\omega x] \exp[j(\omega t - \beta z)],
\]

and for \( x < 0 \), they are given by

\[
H_{j1} = H_{j10} \exp[h_1 x] \exp[j(\omega t - \beta z)],
\]

\[
h_1 = \sqrt{\beta^2 - k_0^2 n_1^2},
\]

\[
E_{z1} = \frac{jh_1}{\omega \sigma_0 n_1^2} H_{j10} \exp[h_1 x] \exp[j(\omega t - \beta z)].
\]

Again similar to the TE mode, the conducting two-dimensional free charge layer with the surface conductivity \( \sigma \) induces an interface current density and imposes a discontinuity in the tangential magnetic field as

\[
H_{j2}(0, z) - H_{j1}(0, z) = \sigma E_{z2}(0, z) - \sigma E_{z1}(0, z).
\]

Similarly, imposing continuity condition of transverse electric field, and the boundary condition given in (4) along with equations (2) and (3), one can easily get the following dispersion equation:

\[
\alpha = \frac{n_2^2}{\sqrt{N^2 - n_2^2}} + \frac{n_2^2}{\sqrt{N^2 - n_2^2}} - \frac{n_2^2}{\sqrt{n_1^2 - n_2^2}},
\]

where \( n_0 \) is intrinsic impedance, \( N \) is the effective index of surface electromagnetic wave or \( \beta/k_0 \), and \( \alpha = j/\sigma_0 n_0 \).

In this case the dispersion equation is only satisfied with \( \text{Im}[\sigma] < 0 \) or \( \alpha > 0 \) where \( \sigma = -\alpha/\sigma_0 \). It should be noted that this case can be implemented by using interface conductivity whose \( f \) factor has positive polarity. Also, it is simple to check that the above results are in agreement with the dispersion equation of surface electromagnetic waves or surface plasmons in the absence of the charge layer with \( \sigma = 0 \) [24].

### 3. SEW in the multilayer structure

To study the effect of conducting interface and surface electromagnetic wave excitation, one has to study multilayer structures in the presence of interface conductivity. This is due to the fact that surface waves are nonradiative, and they cannot be excited by direct illumination of dielectric–dielectric interface. Thus, a general multilayer structure is discussed here, and two important cases, which may be utilized for designing miscellaneous optical devices, are explored thoroughly.

In order to investigate SEWs in multilayer structures, one can use modified transfer matrices [23]. This method provides an efficient evaluation of electromagnetic fields in layered structure through multiplication of \( 2 \times 2 \) matrices corresponding to each layer. Following the discussion given in [23], it is an easy task to exactly evaluate the fields in all layers. If one knows the fields in one of the layers, say the nth layer, then the fields in the mth layer \( (m \neq n) \) can be found by using

\[
\begin{bmatrix}
U_m^t \\
U_m^d
\end{bmatrix} = Q_{n \rightarrow m} \begin{bmatrix}
U_n^t \\
U_n^d
\end{bmatrix},
\]

where \( U \) represents either the electric \( E \) or the magnetic \( H \) field, respectively for TE or TM modes, and

\[
Q_{n \rightarrow m} = Q_m \cdots Q_{m+1} \cdots Q_{m+2} Q_{m\rightarrow m+1}, \quad \text{if } m > n,
\]

\[
Q_{n \rightarrow m} = (Q_{m+1} \cdots Q_{m+2} Q_{m\rightarrow m+1}^{-1}) \cdots Q_{m+1} \cdots Q_{m+2} Q_{m\rightarrow m+1}, \quad \text{if } m < n.
\]

Here \( Q \) matrices are modified transfer matrices reported in [23], and \( U^t, U^d \) are constant complex phasors representing the upward and downward travelling waves.

Using the transfer matrix of the system, one can get reflection and transmission coefficients easily [23, 25]. The overall transfer matrix is not only useful to calculate reflection and transmission coefficients, but also can be used to extract eigenmodes of layered structure [26]. This approach can be used to extract eigenmodes of layered structure in the presence of interface conductivity.

#### 3.1. SEW excitation using four dielectric structure

The excitation of SEW occurs in the region of total internal reflection at the interface of the two dielectrics supporting it. Because phase matching condition must be fulfilled in order to excite SEW, structures such as Kretschmann–Raether configuration or Otto configuration are needed. Adapting the Kretschmann–Raether configuration, and using Fresnel expression for alternative layers [27], the total amplitude reflection coefficient is given as

\[
r_{\text{tot}} = \frac{r_F + r_F}{1 + r_F r_T},
\]
where \( r \) is the amplitude reflection at the base layers (dielectric–dielectric interface supporting SEW), \( r_F \) is the Fresnel reflection coefficient at the outer interface, and \( r_{tot} \) is the total amplitude reflection coefficient. Using the fact that Kretschmann–Raether configuration excites SEW, no abrupt change in amplitude reflection is observed by excitation of SEW in this structure. In order to solve this problem, as shown in figure 2 [28], another layer has been added to the ordinary SEW in this structure. In order to program SEW excitation by using interface conductivity. Figure 3. Surface wave propagation on one-dimensional photonic crystal. The photonic crystal located at \( z < 0 \) with a conducting layer on top is terminated to a cover layer at \( z = 0 \).

where \( n(z) = n(z + m\Lambda) \), and \( m = 1, 2, \ldots \) as shown in figure 3. It is also assumed that there is an interface conductivity at the interface of the multilayer structure and the top layer with the refractive index of \( n_a \). The electric field within each homogeneous layer at the right half space can be expressed as the sum of an incident and a reflected plane wave. The complex amplitudes of these two waves constitute the components of a column vector; therefore, the electric field in layer \( p \) \((p = 1, 2)\) of the \( n \)th unit cell can be represented by \((a_n^{(p)}, b_n^{(p)})^T\), \( p = 1, 2 \). As a result, the electric field distribution in the same layer can be written as

\[
E(y, z) = [a_n^{(p)} \exp(-jk_{pc}(z - (n - 1)\Lambda))] + b_n^{(p)} \exp(jk_{pc}(z - (n - 1)\Lambda))] \exp(-jk_{1}y) \tag{15}
\]

Applying the boundary condition, and imposing the continuity of transverse electric field and transverse magnetic field for the layers inside the photonic crystal (layers without the interface conductivity), or following the procedure of transfer matrix calculations, one can get the following system of equations

\[
\begin{pmatrix}
c_{n+1} \\
d_{n+1}
\end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} c_n \\
d_n
\end{pmatrix},
\]

where \( c_n \) and \( d_n \) are defined as \( a_n^{(2)} \) and \( b_n^{(2)} \) in (2). The matrix elements of this transfer matrix are given by

\[
A = \exp[-jk_{2z},b] \left[ \cos(k_{1z},a) - \frac{i}{2} \left( \frac{k_{1z}}{k_{2z}} + \frac{k_{2z}}{k_{1z}} \right) \sin(k_{1z},a) \right], \tag{17a}
\]

\[
B = -\frac{i}{2} \left( \frac{k_{1z}}{k_{2z}} - \frac{k_{2z}}{k_{1z}} \right) \exp[jk_{2z}b] \sin(k_{1z},a), \tag{17b}
\]

\[
C = \frac{j}{2} \left( \frac{k_{1z}}{k_{2z}} - \frac{k_{2z}}{k_{1z}} \right) \exp[-jk_{2z}b] \sin(k_{1z},a), \tag{17c}
\]

\[
D = \exp[jk_{2z}b] \left[ \cos(k_{1z},a) + \frac{j}{2} \left( \frac{k_{1z}}{k_{2z}} + \frac{k_{2z}}{k_{1z}} \right) \sin(k_{1z},a) \right]. \tag{17d}
\]
In addition to the ordinary boundary conditions, which are implied in the preceding transfer matrix, the periodic boundary condition should also be applied. According to the Bloch theorem [35, 36], the periodic boundary condition is simply given by

\[
\left( \frac{c_{n+1}}{d_{n+1}} \right) = \exp[-j k \Lambda] \left( \frac{c_n}{d_n} \right).
\]  

Regarding equations (16) and (18), the eigenvalue of the transfer matrix given in (17) is the same as the phase vector \( \exp[-j k \Lambda] \). Thus, the solution of \( k \), the Bloch wave propagation constant, can be easily derived as [37]

\[
k(k_y, \omega) = \frac{1}{\Lambda} \cos^{-1} \left( \frac{1}{2} (A + D) \right),
\]  

and the eigenvectors corresponding to the eigenvalues are given by

\[
\left( \frac{c_1}{d_1} \right) = \left( \begin{array}{c} B \\ -A + \exp[-j k \Lambda] \end{array} \right). 
\]  

Equations (15), (19) and (20) along with Maxwell’s equations completely determine the electric and magnetic fields at the right half space or \( z > 0 \). In the left half space or \( z < 0 \), one can use Maxwell’s equations and write

\[
E_y = E_0 \exp[h y] \exp[-j k_y y] \\
H_z = -j \frac{E_{zh}}{\omega \mu_0} \exp[h y] \exp[-j k_y y],
\]  

\[
h = \left( k_y^2 - \left( \frac{\omega n}{c} \right)^2 \right)^{1/2}.
\]

Now boundary condition at \( z = 0 \) must be applied:

\[
H_z - (0, z) - H_z + (0, z) = \sigma E_y - (0, z) = \sigma E_y + (0, z),
\]

where subscripts + and − stand for right and left half spaces, respectively. Applying boundary conditions implied in (22) yields the dispersion equation of surface electromagnetic waves

\[
j \left( \frac{h - \omega}{c} \right) = k_n^2 \left( \frac{B + A - \exp[-j k \Lambda]}{B - A + \exp[-j k \Lambda]} \right),
\]  

\[
\alpha = j \sigma \sqrt{\frac{\mu_0}{\varepsilon_0}},
\]

where \( A \) and \( B \) are defined in equations (17a) and (17b), respectively.

Regarding the dispersion equation (23), it is obvious that \( \alpha \) enables programming the surface wave excitation. This ability has great importance in constructing programmable optical devices. Some examples are given in section 4. It should be noted that in order to excite these nonradiative SEW modes, one can use Kretschmann–Raether configuration as shown in figure 4.

4. Numerical examples

As a test case for electromagnetic surface states on one-dimensional photonic crystals in the presence of interface conductivity, an electromagnetic wave with free space wavelength of \( \lambda_0 = 11.5 \ \mu m \) is considered. For this case \( n_1 = 3.4, \ n_2 = 3.6, \ \sigma = 0, \ a = b = \Lambda/2 = 10 \ \mu m \) and \( n_a = 1.5 \). It can be easily shown that two surface states with \( k_y = 2.639 \) and \( k_y = 3.293 \) exist for this case. Referring to figure 4 with \( n_a = 4 \) and \( X = 1.5 \ \mu m \), reflection coefficients show a deep and narrow dip at an angle of \( \theta = 41.29^\circ \), corresponding to the first electromagnetic surface state. Such dips are observed only in the presence of surface electromagnetic waves. Figure 5 shows reflection coefficients versus different wavelengths for \( \alpha = -0.5, 0, 0.5 \), where \( \alpha \) is defined as \( \alpha = j \sigma \eta_0 \). It is shown that at \( \alpha = 0 \), there is a dip at \( \lambda_0 = 11.5 \ \mu m \). Changing \( \alpha \) yields tuning ability of those filters. These kinds of filters may be found very useful in optical communication and WDMA applications.

As another example for this case, interface conductivity can be used to modulate reflection and transmission coefficients. Figure 6 shows reflection coefficients versus \( \alpha \) (proportional to interface conductivity as indicated previously) at \( \lambda_0 = 11.5 \ \mu m \). This figure shows us how the changes of the interface conductivity can affect reflection coefficient. This case demonstrates the capability of the structure shown in figure 4 when used as an optical modulator. Interface
conductivity may be tuned by applying a transverse voltage. This case can also be utilized as an optical switch.

As a test case for excitation of electromagnetic surface states in the presence of interface conductivity using modified Kretschmann–Raether configuration shown in figure 2, an electromagnetic wave with free space wavelength of $\lambda_0 = 10.6 \, \mu\text{m}$ is considered. In this case $n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$, and $\alpha = 1$. As long as $\text{Im}[\sigma] < 0$, only TM mode surface waves are supported by this structure. Transmission coefficients of this structure are shown for different incident angles in figure 7. A deep and narrow dip in reflection coefficient is observed due to the efficient interaction between the surface conductivity and electromagnetic fields, and the excitation of SEW. Such dips are observed only in the presence of surface conductivity. Transmission coefficients of this structure do not show such a dip when illuminated by TE mode waves. Figure 8 shows reflection and transmission coefficients versus interface conductivity when incident angle is fixed at 75.73°. Analysis of this structure shows that small changes in surface conductivity make abrupt changes in reflection and transmission coefficients. This property can be used for constructing optical modulators and optical switches. Figure 9 shows reflection and transmission coefficients versus the incident angle, when incident angle is fixed at 75.73° and $\alpha = 1$. This figure demonstrates the feasibility of making optical filters based on the interaction of electromagnetic fields and surface conductivity.

As previously stated in section 3.1, increasing $X_1$ and $X_2$ makes structure shown in figure 2 closer to that shown in figure 1. Thus, similar computations with $X_1 = X_2 = 3 \, \mu\text{m}$ must be more sensitive compared to the tested structure with $X_1 = X_2 = 1 \, \mu\text{m}$. Numerical computations confirm this assertion. Figure 10 shows reflection and transmission coefficients versus the incident angle for this case. It is obvious that the latter case is more sensitive. It is interesting to note that the narrow highly deep response observed in the reflection occurs at an incident angle in which its $k_i$ is matched with $k_i = k_0N$, where $N$ is obtained from (10), the dispersion equation of surface wave. This case is more appropriate for filter applications. Figure 11 shows the variations of reflection and transmission coefficients versus the wavelength of the incident wave, when the incident angle is fixed at 70.575°, and $\alpha = 1$. 

Figure 6. Optical modulation using interface conductivity: reflection coefficients versus $\alpha$ (proportional to the interface conductivity as described previously) at the wavelength of $\lambda_0 = 11.5 \, \mu\text{m}$.

Figure 7. Reflection (solid) and transmission (dashed) coefficients of the structure shown in figure 2 versus the incident angle. Low sensitivity case: $\lambda_0 = 10.6 \, \mu\text{m}, n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$ and $\alpha = 1$.

Figure 8. Reflection (solid) and transmission (dashed) coefficients of the structure shown in figure 2 versus interface conductivity ($\sigma$). Low sensitivity case: $\lambda_0 = 10.6 \, \mu\text{m}, n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$ and $\theta = 75.73°$.

Figure 9. Reflection (solid) and transmission (dashed) coefficients of the structure shown in figure 2 versus wavelength. Low sensitivity case: $\sigma = 1, n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$ and $\theta = 75.73°$. 

Figure 10. Reflection and transmission coefficients as a function of $X_1$ and $X_2$. Low sensitivity case: $\lambda_0 = 10.6 \, \mu\text{m}, n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$ and $\theta = 75.73°$. 

Figure 11. Reflection and transmission coefficients as a function of wavelength and $X_1$ and $X_2$. Low sensitivity case: $\sigma = 1, n_a = n_b = 3.84, n_1 = n_2 = 1.3, X_1 = X_2 = 1 \, \mu\text{m}$ and $\theta = 75.73°$. 

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applied transverse voltage, the feasibility of achieving guided-attractive applications. Examples show some interesting features, which can have been given to support the idea of achieving a tunable filter. In very sharp filter applications, one should also take into account the frequency dependence of the interface conductivity.

5. Conclusions

The possibility of SEW propagation at the interface of two dielectrics in the presence of two-dimensional free charges or interface conductivity has been explored. The calculations have been separately done for basic TM and TE polarized SEWs, and their dispersion equations are derived. Also, an efficient algorithm for Fresnel reflection or transmission coefficients along with an approach for extraction of dispersion equation of multilayer structures in the presence of interface conductivity has been explored. The calculations have been thoroughly examined and the numerical results have been given. These examples show some interesting features, which can have attractive applications.

By controlling the density of the interface charges with an applied transverse voltage, the feasibility of achieving guided-mode resonance of SEWs, modulation, switching and tunable optical filtering has been demonstrated. Several examples have been given to support the idea of achieving a tunable filter. The possibility of SEW propagation at the interface of two dielectrics in the presence of two-dimensional free charges or interface conductivity has been explored. The calculations have been separately done for basic TM and TE polarized SEWs, and their dispersion equations are derived. Also, an efficient algorithm for Fresnel reflection or transmission coefficients along with an approach for extraction of dispersion equation of multilayer structures in the presence of interface conductivity has been explored. The calculations have been thoroughly examined and the numerical results have been given. These examples show some interesting features, which can have attractive applications.

By controlling the density of the interface charges with an applied transverse voltage, the feasibility of achieving guided-mode resonance of SEWs, modulation, switching and tunable optical filtering has been demonstrated. Several examples have been given to support the idea of achieving a tunable filter. In very sharp filter applications, one should also take into account the frequency dependence of the interface conductivity.

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