Traveling plasmon interaction with light

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1. Introduction:
One of the fundamental challenges in photonics integration, compared to electronics, is the large variety of devices. While electronics consist mainly of two devices, i.e., transistors and interconnects, quite a few devices have to be implemented to construct circuits in photonics, such as light emitter, modulator, multiplexer/demultiplexer, photodetector, isolator and interconnect. Based on coupling the Maxwell’s equations with electron motions, it has been predicted that a light mode in conductive waveguides should strongly interact with the traveling plasmons and should show amplification. Thus, this could be an important cornerstone for silicon photonics. This paper briefly a couple of key interactions of light with electrons according to the electron density and its relative velocity to light.

2. Theory
An analytical solution of the coupled Maxwell’s equations with traveling plasmons is shown by a secular equation and simplified to a form of \((\omega - \beta k)^2 - \omega_\text{p}^2)((kc)^2 - \omega^2 + \omega_\text{p}^2 + \omega_\text{r}^2) + \beta^2 \omega_\text{p}^2 \omega_\text{r}^2 = 0\). Here, \(\omega\) denotes the mode frequency; \(k\) the mode propagation constant; \(\beta\) the ratio of velocity of the electrons and light, \(\omega_\text{p}\) the plasma frequency, and \(\omega_\text{r}\) the cutoff frequency of the waveguides. This equation indicates that a coupling of the traveling plasmon and the waveguide mode mediated by a term of \(\beta^2 \omega_\text{p}^2 \omega_\text{r}^2\) generates the optical wave could travel at an apparently forbidden frequency zone \((\omega < \omega_\text{r})\) carried by the interaction with electrons. This plasmon instability is due to perturbation by the current. No instability is found when no current is applied.

3. Calculations
A basic mode with the form of \(E_\omega(x, y, z) = e^{kz} E_\omega(x, y) e^{-i(k_z \omega - kc z)}\) is obtained from the maxwell equation with an amplifying part of \(e^{kz}\). While a large amplification is predicted, an extremely tiny \(k_z\) will cause huge evanescence and loss. We normalized the equation as follows to estimate the exact amplification: \((\omega - \beta k)^2 - (\omega^2 + \omega_\text{r}^2 + k^2) + \beta^2 k^2 = 0\) and \(k\) as parameters. Here, \(\omega\) is real and \(k = k_\text{r} + ik_\text{i}\). As in Figs. 1 and 2, the real and imaginary parts linearly depend on \(\beta\) and \(\kappa\), suggesting that higher \(\kappa\) and \(\beta\) are favorable for interaction. \(\beta\) is basically limited by the electron drifting velocity, while slow light using photonic structures should increase \(\beta\). \(\kappa(\omega_\text{r}\text{in non-normalized case})\) is decisive for amplification.

4. Conclusions
Coupled Maxwell’s equations with electron motion generates instability of light wave and traveling plasmons which could lead amplification of the light wave in conductive waveguide. Silicon photonics provides a fundamental test bed to understand the predictions experimentally.

参考文献