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Electromagnetic phenomena in time-modulated metasurfaces

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Abstract – In this talk we will review our recent results on surface waves on time-varying boundaries. We consider boundaries with spatially uniform but time-modulated macroscopic reactive surface impedance. Analytical results and numerical simulations reveal possibilities to amplify surface waves, nearly stop their propagation, convert them to waves propagating in space, and other interesting effects. First experimental results confirm the amplification effect.

I. INTRODUCTION

In recent years, there has been a strong renewed interest to electromagnetic phenomena in non-stationary, time-varying media [1, 2]. Especial interest has been paid to the so-called space-time photonic crystals, where the modulation of material parameters is periodic in time. Also, phenomena at sudden changes of medium properties in time have been considered, e.g. [3]. So far, only a few studies considered effects on time-modulated boundaries and metasurfaces [4, 5], where interplays of inhomogeneities in both space and time can lead to novel wave phenomena. Here, we consider surface waves on reactive boundaries (Fig. 1, left) that are uniform in space but varying in time. Although the surface itself is assumed to be spatially homogeneous (in the macroscopic sense), the presence of a boundary with free space makes the system inhomogeneous also in space.

![Fig. 1: A TE-polarized surface wave which is propagating along an impenetrable capacitive boundary and the corresponding dispersion relation.](image)

The dispersion relation for surface waves on reactive boundaries is well known, and the corresponding dispersion curves for capacitive boundaries are shown in Fig. 1, right. The analysis of the plot suggests that variations of the surface capacitance can allow wave amplification, coupling between surface mode and propagating waves, and “freezing” surface-wave propagation, as illustrated by arrows.

II. TIME-PERIODICAL MODULATIONS

First we assume that the surface properties of a capacitive boundary periodically changes in time, remaining uniform over the surface. The fundamental modulation frequency we denote by $\omega_M$. The eigenmode with a certain
Fig. 2: Left: Dispersion relation of a time-varying capacitive sheet (blue curve), the horizontal axis is the normalized wavevector. Right: Field distribution of $E_z$ at $t = 20T_0$ (external excitation is on and modulation is off), $t = 39T_0$ (external excitation is off and modulation is on), and $t = 50T_0$ (both external excitation and modulation are off).

The propagation constant $\beta$ will contain components at frequencies $\omega_n = \omega + n\omega_M$, $n = 0, \pm 1, \pm 2, \ldots$. Satisfying the impedance boundary condition, it is possible to numerically find frequencies $\omega$ that satisfy the dispersion relation for given values of the propagation constant $\beta$. Figure 2 (left) shows the dispersion curves assuming that the surface is modulated harmonically [6].

Inside the bandgap, shown as a red region, the eigenfrequencies are complex-valued. In the assumption of $exp(j\omega t)$ time dependence, positive imaginary part means that the wave is exponentially decaying in time, and negative imaginary part means that the wave is exponentially growing in time. This property allows amplification of surface waves by external modulation at a frequency corresponding to a bandgap. Example numerical simulations are shown in Fig. 2 (right). In contrast to conventional parametric amplification, there is no need for synchronization of the pump frequency and phase with the incident wave.

III. ABRUPT CHANGES

Next, we investigate scattering of surface waves on reactive boundaries when the surface properties quickly change in time. These investigations reveal several exotic wave phenomena. First, by switching the effective capacitance of the boundary from a low to a high value, the surface wave is slowed down and effectively frozen. Second, returning to the initial state, the power carried by the surface wave is strongly amplified. Furthermore, temporal jumps of the boundary impedance couple free-space propagating waves to the surface wave. Reciprocally, it is also possible to fully convert a surface wave to free-space propagating waves switching from a boundary supporting the orthogonal polarization.

Assuming that the surface capacitance rapidly changes at $t = 0$ and using the time-jump boundary conditions

$$D_{t=0^-} = D_{t=0^+}, \quad B_{t=0^-} = B_{t=0^+}$$

(note that not only the tangential components, but the total vectors are continuous), it is possible to analytically find the amplitude of forward and backward surface waves after the jump.

Figure 3 (left) shows a numerical example that corresponds to creation of a super-slow surface wave (“frozen” wave). In this example, we assume that the surface capacitance changes from $C_0 = 0.1 \text{ pF}$ to $C_1 = 1000 \text{ pF}$, and $\beta = 153 \text{ m}^{-1}$. The corresponding eigenfrequencies are $\omega_0/(2\pi) = 4.83 \text{ GHz}$ and $\omega_1/(2\pi) = 0.055 \text{ GHz}$. Distributions of magnetic field at the surface, $H_x$, are shown before and after the temporal jump. The magnetic field amplitude dramatically increases after the jump, and the total energy of the system significantly increases. We position two probes [probe A and probe B in Fig. 3(b)] on the boundary. Probes A and B are placed at the antinodes (maxima) of $E_y$ and $H_x$, respectively. The time-varying electric field at probe A and magnetic field at probe B are plotted in Fig. 3 (right). The oscillation frequency of fields after the jump ($t > 0$) is dramatically reduced, while the propagation constant $\beta$ remains unchanged. This result clearly demonstrates that the reflected and transmitted waves are ultra-slow, both in terms of the phase and group velocities.
Fig. 3: Left: Spatial distributions of magnetic fields $\mathbf{H}_x$ at (a) $t = 0^-$, (b) $t = 0.006T_1$, and (c) $t = 0.26T_1$. Right: Temporal variations of $E_y$ at probe A and $H_x$ at probe B. The fields are normalized by their incident amplitudes. $T_1$ is the period of slow oscillations after the capacitance jump.

In the presentation, we will discuss also other interesting effects at temporal discontinuities of boundaries. Furthermore, we will present our first experimental results in the microwave frequency range. We think that these effects may open up new possibilities for generation and control of surface waves.

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