

Optical Dyakonov surface waves at magnetic interfaces

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We address the existence and properties of lossless surface waves that form at interfaces between magnetic and birefringent media. We show that the angular domain of existence of Dyakonov surface waves for magnetic interfaces is significantly larger than that for nonmagnetic ones. Our results have important implications for the experimental generation of surface waves and for their potential applications based on guided-to-leaky transitions. © 2005 Optical Society of America
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Optical surface waves, i.e., light wave packets localized at the interface between two media with different properties, are a topic of continually increasing interest because of their fundamental properties as well as potential applications, e.g., in sensing, trapping, and imaging, based on near-field techniques. Research has been focused mostly on surface waves and resonances that form at metal–dielectric interfaces, so-called surface plasmons,¹ and more recently in photonic crystals.² However, surface waves can also form at the interfaces between two homogeneous dielectrics, provided that at least one of the dielectrics is birefringent, as was theoretically discovered by Dyakonov almost two decades ago.³ In contrast to plasmons, such surface waves exist in transparent media; thus they are lossless. The special conditions at which Dyakonov resonances are found to exist in all the geometries addressed to date^{3–8} are not easy to meet in practice. Therefore elucidation of strategies to enhance the existence domains is of capital importance for exploiting the properties of surface waves. One avenue opened recently is the use of the tunable properties of photonic metamaterials.⁹ In this Letter we use a different approach, studying, for the first time to our knowledge, Dyakonov waves in magnetic materials. The results reveal that the existence domains are enhanced compared with those encountered in nonmagnetic materials in both interface^{3,4,8} and nanolayer structures.^{5–7} A motivation for this study is the recent development of transparent materials, such as aerogels¹⁰ and molecular-based magnets,¹¹ which under proper conditions can exhibit moderately large permeability values (i.e., $\mu_r \approx 2$). In addition, the use of the metamaterials' magnetic properties¹² can also open important prospects and potential applications for Dyakonov surface waves.

Dyakonov surface waves form at interfaces between dielectric homogeneous media and birefringent media under special conditions, namely, when (i) the birefringent crystal is either positive uniaxial or biaxial, (ii) the angle between the optical axis of the birefringent crystal and the propagation axis of the surface wave falls within a small acceptance range, and, for a uniaxial material, (iii) the value of the refractive index of the isotropic material lies between those of the ordinary (O) and the extraordinary (E)

waves of the birefringent material. Here we show how interfaces between materials with magnetic properties affect the allowed regions of surface wave existence set by those conditions.

We consider a planar geometry with isotropic cladding on top of a birefringent material with the interface plane at $z=0$. The surface wave propagates in the x direction, with evanescent fields exhibiting exponential z decay in both the cladding and the substrate. Let $\epsilon_{c,os,es}$ be the relative permittivities that correspond to the cladding and the O and E waves in the materials. $\mu_{c,s}$ are the corresponding relative permeabilities. Then the refractive indices are $n_c^2 = \epsilon_c \mu_c$ and $n_{os,es}^2 = \epsilon_{os,es} \mu_s$. Equal permeabilities for the O and E waves in the birefringent medium are assumed. Here we consider only uniaxial birefringent substrates with the optical axis parallel to the (x,y) plane at an angle θ with respect to propagation direction x . Let k_0 be the vacuum wave number and N be the effective index of the guiding surface mode. Starting from the wave equation in a birefringent medium, $\nabla^2 \mathbf{E} + k_0^2 \hat{\epsilon} \mathbf{E} = \nabla(\nabla \cdot \mathbf{E})$, where $\mathbf{E}(x,z) = (E_x, E_y, E_z)^T$ is the electric field and $\hat{\epsilon}$ is the permittivity tensor whose nonvanishing elements are $\epsilon_{xx} = n_{os}^2 \sin^2 \theta + n_{es}^2 \cos^2 \theta$, $\epsilon_{yy} = n_{os}^2 \cos^2 \theta + n_{es}^2 \sin^2 \theta$, $\epsilon_{zz} = n_{os}^2$ and $\epsilon_{xy} = \epsilon_{yx} = (n_{es}^2 - n_{os}^2) \sin \theta \cos \theta$, we have obtained the electromagnetic decaying eigenmodes of the homogeneous magnetic cladding and of the birefringent substrate. By applying boundary conditions at the cladding and the substrate, we obtained the eigenvalue equation of the surface guided modes as

$$n_{os}^2 A_e B_o \sin^2 \theta - \gamma_{os}^2 A_o B_e \cos^2 \theta = 0, \quad (1)$$

where $A_{o,e} = \gamma_{os,es} / \mu_s + \gamma_c / \mu_c$, $B_o = n_c^2 \gamma_{os} / \mu_c + n_{os}^2 \gamma_c / \mu_s$, and $B_e = n_c^2 \gamma_{os} / \mu_c + n_{os}^2 \gamma_{es} \gamma_c / (\mu_s \gamma_{os})$, with $\gamma_c = (N^2 - \epsilon_c \mu_c)^{1/2}$, $\gamma_{os}^2 = N^2 - \epsilon_{os} \mu_s$, $\gamma_{es}^2 = n_{es}^2 [N^2 - n_{es}^2(\theta)] / n_{es}^2(\theta)$, and $n_{es}^2(\theta) = n_{os}^2 n_{es}^2 / (n_{os}^2 \sin^2 \theta + n_{es}^2 \cos^2 \theta)$.

An inspection of eigenvalue equation (1) reveals that for fixed refractive indices its solutions depend on the ratio of the relative magnetic permeabilities $r = \mu_c / \mu_s$ and not on μ_c and μ_s independently. This means, in particular, that one gets the same solutions for an interface that separates two right-handed materials as for one that separates two left-handed ma-

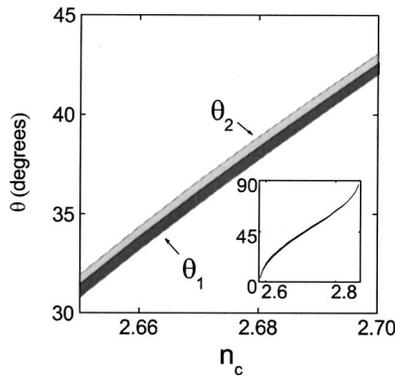


Fig. 1. Detail from the existence domain in the (n_c, θ) parameter plane for a rutile substrate ($n_{os}=2.583$, $n_{es}=2.865$), for nonmagnetic cladding (darker shaded region), and for magnetic cladding with $r=2$ (darker and lighter shaded regions). For completeness, the inset shows the whole existence domain for the magnetic case.

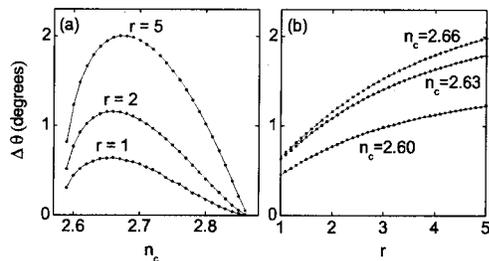


Fig. 2. (a) Angular existence window $\Delta\theta$ versus n_c for three representative values of r . (b) $\Delta\theta$ versus r for three representative values of n_c . For both figures the substrate was rutile.

materials. In contrast, new field distributions are expected for the interface between a left-handed and a right-handed material; we are studying this possibility.

We show in Fig. 1 the existence domains of the Dyakonov waves both for a nonmagnetic case ($\mu_c = \mu_s = r = 1$) and for a case when magnetic cladding ($\mu_c \neq 1$, $r \neq 1$) is considered. To illustrate the point, in both cases the substrate was rutile. For a given cladding refractive index n_c , Dyakonov waves are allowed to exist for orientations of the optical axis that belong to the angular existence interval $\Delta\theta = \theta_2 - \theta_1$. The two limiting angles $\theta_{1,2}$ correspond to the cutoff conditions $N = n_c$ and $N = n_{es}(\theta)$, respectively. The important result shown by Fig. 1 is that the existence, in the (n_c, θ) parameter plane, of the Dyakonov surface waves for magnetic interfaces, which corresponds to the darker and lighter shaded regions in Fig. 1, is wider than that which corresponds to a nonmagnetic cladding (darker shaded region only). This is so mainly because of the relaxation of the cutoff condition at θ_2 , while θ_1 remains almost independent of r .

The angular domain of existence of the Dyakonov waves depends also on the cover's refractive index, n_c , for a given value of permeability μ_c . We have thoroughly investigated this dependence for a few representative values of relative permeability ratio r . Results are shown in Fig. 2(a). For all the cases

considered, there exist optimal values of n_c that ensure maximal $\Delta\theta$, while $\Delta\theta$ decreases when n_c approaches cutoff value n_{os} or $n_{es}(\theta)$. This figure also shows that the higher r is (i.e., the higher parameter μ_c is), the higher the optimal n_c . The $\Delta\theta$ increment in terms of r can also be observed in Fig. 2(b). Here n_c is kept constant and equal to three representative values and r is varied by use of the same substrate as above. For all the cases that we have considered here, a monotonic increase of $\Delta\theta$ with r is observed. This enhancement is proportional to the initial $\Delta\theta$ in a nonmagnetic case. To check this point, we calculated the existence domain for an interface between a photonic crystal substrate and a magnetic cladding. This arrangement, operating in the homogenized limit, could, depending on its geometry, exhibit a large birefringence, up to $\Delta n = 0.6$ ($n_{os} = 1.35$ and $n_{es} = 1.92$).⁹ The existence domain with $n_c = 1.55$ in the case of a nonmagnetic cladding ($r = 1$) is $\Delta\theta \approx 5^\circ$. This value was almost doubled $\Delta\theta \approx 9.7^\circ$, for a magnetic cladding with $r = 5$, a result that is in accordance with those shown in Fig. 2(b) for the rutile case.

A parameter that characterizes the localization of the surface wave is the so-called penetration depth, defined as $\Gamma_x = \lambda / (2\pi\gamma_x)$, with $x = c, Es$. As Fig. 3 shows, penetration depths of the order of λ are achieved near the center of $\Delta\theta$, while the wave becomes increasingly more delocalized as one approaches cutoff angles θ_1 and θ_2 . The figure also shows how the $\Delta\theta$ increment with r affects Γ_x . In particular, it can be seen that, for a fixed value of θ , the penetration depth in the birefringent crystal decreases with r , in this way increasing the range of angles at which Dyakonov waves are localized near the interface.

In what follows, we consider the properties of the Dyakonov waves extended to sandwichlike structures that contain an isotropic nanolayer as a film between the birefringent substrate and the cladding. Because of the presence of the Dyakonov resonances, such structures support guided waves for film thicknesses well below the usual waveguide cutoff. This results in an enhancement of the angular domain of existence for guided waves compared with that for surface waves. We found that, for certain parameters, a significant enhancement of the existence domain is afforded by the nanolayer when the cladding is a magnetic material. We present a comparison of the

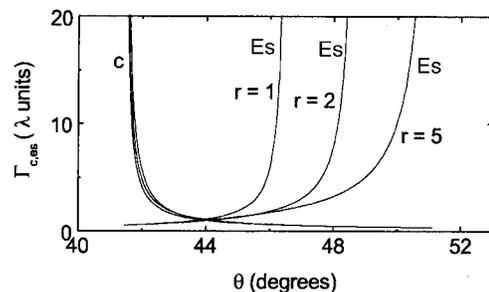


Fig. 3. Cladding and substrate penetration depths $\Gamma_{c,Es}$ versus orientation angle θ for a few representative relative permeabilities r . Here $n_c = 1.55$, $n_{os} = 1.35$, and $n_{es} = 1.92$ (the substrate is a photonic crystal).

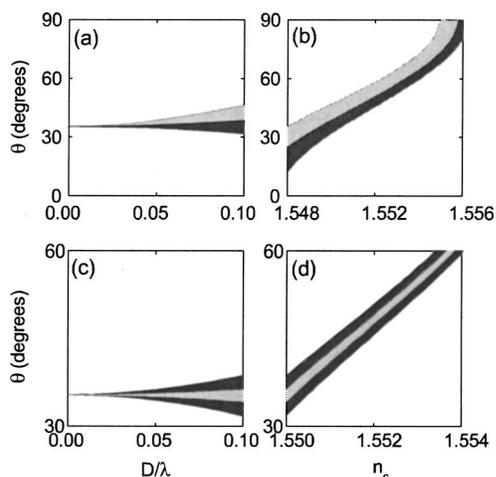


Fig. 4. Angular existence domains of Dyakonov-type hybrid guided waves versus (a) normalized film thickness D/λ and (b) n_c , for both magnetic cladding with $\mu_c=2$ (darker and lighter shaded regions) and nonmagnetic cladding (darker shaded regions only). Angular existence domains of the Dyakonov-type guided waves versus (c) D/λ and (d) n_c for both a magnetic film ($\mu_f=2$; lighter shaded regions only) and a nonmagnetic film (lighter and darker shaded regions) between nonmagnetic cladding and substrate. In (a) and (c) $n_c=1.55$; in (b) and (d) $D/\lambda=0.1$.

magnetic and nonmagnetic cladding cases in Figs. 4(a) and 4(b) for a quartz crystal substrate ($n_{os}=1.547$ and $n_{es}=1.556$) and a film with $n_f=1.57$. One gets, for a cladding with a moderate permeability ($r=2$), angular existence domains for Dyakonov-type guided waves that are more than two times larger than those that correspond to nonmagnetic claddings.

Our analysis also indicates that Dyakonov-type guided waves are supported by magnetic ultrathin films between a nonmagnetic isotropic cladding and a nonmagnetic birefringent substrate. Contrary to the previous case, for moderate values of film permeability the existence domain is smaller than that which corresponds to the Dyakonov-type guided waves that form for a nonmagnetic film [see, e.g., Figs. 4(c) and 4(d)]. However, from the point of view of potential applications, the last structure could be interesting for probing the properties of ultrathin films of magnetic materials deposited on top of a substrate, acting as biological or chemical sensors based on guided-to-leaky transitions.

It is worth noting that for both sandwich-type geometries that we analyzed here (magnetic cladding–nonmagnetic film and nonmagnetic cladding–magnetic film), we have shown in Fig. 4 only the existence regions that correspond to the single-mode regime. Smaller values of n_c allow for simultaneous propagation of two guided modes, one of them of a Dyakonov type, that is, a TE-dominant mode, whereas the other mode is a TM-dominant one that branches from the pure TM mode that exists at $\theta=0$. Moreover, because of the presence of the ultrathin film, the Dyakonov-type guided waves can exist for conditions outside the limit $n_{os} < n_c < n_{es}$. In particular, they can exist even in the absence of a material

cladding, i.e., for an air–ultrathin magnetic film–birefringent substrate geometry. The importance of this result in view of potential applications of the surface waves to interrogate properties of nanolayers is clearly apparent.

In summary, we have shown that interfaces between a birefringent substrate and a magnetic cladding exhibit favorable conditions for the formation of Dyakonov surface waves. We found that the angular existence domain of these waves is enhanced compared with nonmagnetic interfaces. The results hold for different geometries, including antiguiding structures.¹³ The concept put forward is important in that it might permit the observation of Dyakonov resonances; it might find applications also in the characterization of nanolayers of chemical and biological materials with magnetic properties,^{14–17} such as fluids of magnetic nanoparticles, as well as in sensing devices based on the unique properties of Dyakonov waves.

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