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Vector discrete nonlinear surface waves

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Abstract: It is theoretically shown that multi-component discrete vector surface waves can exist in arrays of coupled waveguides. These mutually trapped surface states primarily reside in the first waveguide of a semi-infinite array. The existence and stability of such surface waves are systematically investigated.

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1. Introduction

In general, surface waves exist along the interface between two different media and on many occasions are known to exhibit behavior that has no analogue in continuous systems. In years past, they have been the focus of many studies in a diverse collection of scientific disciplines such as physics, chemistry, and biology [1]. Perhaps the best known example of such surface states, in the linear optical domain, are plasmon waves, which exist at metal/dielectric interfaces [1]. In addition, optical surface waves can also propagate along the boundary of semi-infinite periodic or multi-layer dielectric media [2] as well as along the interfaces between anisotropic materials [3]. Material nonlinearity is another mechanism through which optical surface waves can exist [4–11]. Several studies have predicted nonlinear TE, TM, and multi-component surface waves along single dielectric interfaces [4]. These works have shown that these waves are strictly a nonlinear phenomenon and have no counterparts in the linear domain. Other studies have investigated nonlinear surface waves in dielectric films [12] and interfaces between photorefractive materials [13, 14]. Unfortunately, due to the difficulties in exciting such waves and because of their high power requirements, work in this area has remained primarily theoretical in nature.

Over the past few years, discrete waveguide arrays have become a topic that has attracted considerable attention [15]. During this period, these periodic structures have been shown to exhibit a wealth of new phenomena that have no analog in continuous systems. In a recent study, semi-infinite waveguide arrays have been suggested as a promising environment in which nonlinear surface wave dynamics can be readily investigated both theoretically and experimentally [16]. In such a configuration, the discrete nonlinear surface wave resides mainly in the first waveguide site of the array and its only possible above a certain power threshold. Many systems, however, such as nonlinear waveguide arrays exhibit birefringence, and as a result, the underlying polarization dynamics must be considered in detail [17–19].

In this Letter, we theoretically investigate the existence of vector discrete surface waves consisting of two coherently coupled orthogonal polarizations in AlGaAs waveguide arrays. We demonstrate that stable propagation can be achieved provided that the two appropriate polarizations (TE/TM) are in-phase when they are launched into the array. In addition to this linearly polarized family, we find that elliptically polarized nonlinear surface states can also exist but happen to be unstable. The stability properties of these waves are in agreement with the Vakhitov-Kolokolov criterion.

2. Statement of the Problem

As a demonstration example, we consider an AlGaAs waveguide array identical to that recently used to observe vector discrete solitons [19]. The operating wavelength is taken to be $\lambda_0 = 1.55 \, \mu m$. Thus, we assume the system is operated below half the semiconductor’s band gap, therefore we can neglect multi-photon absorption effects. At this wavelength, the effective cross-sectional area of each waveguide in this array is $A_{\text{eff}} = 4.7 \, \mu m^2$ and the coupling coefficient between adjacent waveguide sites is $\kappa = 0.336 \, mm^{-1}$. In addition, the nonlinear Kerr coefficient is taken to be $\hat{n}_2 = 1.5 \times 10^{-13} \, cm^2/W$ and the linear birefringence in every channel is $n_x - n_y = 1.8 \times 10^{-4}$. For the purposes of this discussion, we will associate the TE polarization with the slow axis ($n_x$).

From coupled mode theory, the discrete field amplitudes of the two orthogonally polarized waves are found to evolve according to the following pair of discrete equations:
\[
\begin{align*}
\frac{da_n}{d\xi} + a_n + \gamma (a_{n+1} + a_{n-1}) + \left[|a_n|^2 + A |b_n|^2\right] a_n + B b_n^2 a_n^n &= 0, \\
\frac{db_n}{d\xi} - b_n + \gamma (b_{n+1} + b_{n-1}) + \left[|b_n|^2 + A |a_n|^2\right] b_n + B a_n^2 b_n^n &= 0.
\end{align*}
\]

In the above equations, \(a_n\) and \(b_n\) are respectively the normalized slowly varying field amplitudes of the TE and TM polarized waves and are related to the actual fields via \((a_n, b_n) = \left[\left(n_2/(n_x - n_y)\right)^{1/2} (E_{nx}, E_{ny})\right]\) for \(n \geq 0\) and \((a_n, b_n) = 0\) for \(n < 0\). The normalized distance \(\xi\) is related to the actual \(z\) coordinate through \(\xi = k_0 z (n_x - n_y) / 2\), and the coupling coefficient \(\gamma\) is normalized with respect to the birefringence, \(\gamma = 2 \kappa / [k_0 (n_x - n_y)]\). The nonlinear Kerr coefficient used in Eqs. (1) is given by \(n_2 = \hat{n}_2 n / 2 \eta_0\), where \(\eta_0\) is the vacuum intrinsic impedance and for this material the refractive index is 3.3. These equations implicitly describe self- and cross-phase modulation (SPM and XPM) and four-wave mixing (FWM) processes. As obtained from the AlGaAs \(\chi^{(3)}\) tensor, the ratio of XPM to SPM is \(A \approx 1\), and the ratio of FWM to SPM is \(B \approx 0.5\). Moreover, the birefringence of the system is reflected in the second terms of Eqs. (1).

3. Solutions and their Stability

In order to identify vector discrete surface wave solutions in this system, we assume that they have the form \((a_n, b_n) = (X_n, Y_n) \exp(iq\xi)\). After substituting these forms into Eqs. (1), the resulting nonlinear difference equations are numerically solved using Newtonian relaxation techniques. After the solutions are obtained, each family is mapped on a \(P - \Delta\) diagram, where \(P = (n_x - n_y) \left(A_{eff}/\hat{n}_2\right) \sum \left(|a_n|^2 + |b_n|^2\right)\) is the total power conveyed by both polarizations in the waveguide array and \(\Delta = (k_0 q / 2) (n_x - n_y)\) is the “eigenvalue” of the surface wave. It is important to note that, for the purposes of this letter, we will limit ourselves to only the most primitive families of vector discrete surface waves. The stability properties of these solutions are then investigated using linear stability analysis.

Fig. 1. \(P - \Delta\) diagrams for the linearly polarized (solid line) and elliptically polarized (dash line) discrete vector surface waves as well as for the scalar TE (dotted line) and TM (dotted-dash line) surface waves.

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We begin our study by first considering single-component (TE or TM polarized) surface states. Due to the birefringence in our system, these singly polarized waves are separate entities and must be explored individually. The existence curves for these two families of discrete surface waves can be seen in the \( P - \Delta \) diagram of Fig. 1. Notice that in both cases there is a point at which the total power conveyed has a minimum. To the left of this minimum the nonlinear surface wave solutions become broader and broader, thus causing the total power conveyed to abruptly increase. A close inspection of the eigenvalues \( \Omega \) associated with field perturbations reveals that these solutions are unstable (left of the minimum) in agreement with the Vakhitov-Kolokolov criterion \( (dP/d\Delta > 0: \text{Stable}; dP/d\Delta < 0: \text{Unstable}) \). As the eigenvalue \( \Delta \) is increased, we find that, in our system, the TE family of one-component discrete surface waves becomes stable at a power level of 164 W or \( \Delta \approx 1.34 \) mm\(^{-1}\). This TE family remains stable up to a critical power of 243 W and \( \Delta \approx 2.01 \) mm\(^{-1}\). At this point, the curve bifurcates into two solution branches as seen in Fig. 1. After the split, the upper branch (dotted line) is the continuation of the now unstable single-component TE family while the lower branch (solid line) corresponds to a new family of stable solutions involving in-phase TE and TM surface components, thus forming a linear polarized vector surface wave. The total power conveyed by the individual TE and TM components of these linearly polarized entities is shown in Fig. 2. It can be clearly seen that for this family of vector surface waves most of the power is in the TE polarization. In the case of TM polarized discrete surface waves, a similar scenario occurs in the \( P - \Delta \) diagram. However, in its range of existence, the entire TM branch is unstable. Note that, as in the TE case, a bifurcation occurs after a critical power of 255 W and \( \Delta \approx 1.31 \) mm\(^{-1}\). After the bifurcation, a new branch corresponding to a family of vector states in which the TE and TM components are out of phase by \( \pi/2 \) emerges. These correspond to elliptically polarized vector surfaces waves. We would also like to compare the vector surfaces waves to those considered earlier in isotropic array systems [16]. In our example, had the array elements been isotropic, the threshold power necessary to establish surfaces states would be approximately 170 W (occurring at \( \Delta = 1.00 \) mm\(^{-1}\)). This is very close the threshold power of the stable TE family.

In the regime where vector discrete surface waves are highly confined, the discrete field amplitudes can be approximated analytically by the following expressions: \( X_n = A_0 \exp(-\nu n) \) and \( Y_n = B_0 \exp(-\mu n) \) for \( n \geq 0 \) and \( X_n = Y_n = 0 \) for \( n < 0 \) where \( \nu = \cosh^{-1}[(q - 1)/2\gamma] \) and
\[ \mu = \cosh^{-1}\left[\frac{(q + 1)}{2\gamma}\right]. \]

The field amplitudes are determined from

\[
A_0^2 = \frac{\gamma[(A \pm B) \exp(\mu) - \exp(\nu)]}{(A \pm B)^2 - 1},
\]

\[
B_0^2 = \frac{\gamma[(A \pm B) \exp(\nu) - \exp(\mu)]}{(A \pm B)^2 - 1},
\]

where the \( \pm \) respectively represents the linearly and elliptically polarized vector surface wave families.

The stable propagation of the TE and TM components of a linearly polarized vector surface wave at \( \Delta \approx 3.6 \text{ mm}^{-1} \) in an AlGaAs waveguide array is shown in Fig. 3. In this case, the total power conveyed in the TE component is 341 W and approximately 111 W in the TM polarization. The stability of this linearly polarized solution is further verified by considering the eigenvalues, \( \Omega \), of the perturbed problem in the complex plane. As can be seen in Figure 3(c), all of the eigenvalues are real, therefore perturbations will not grow, and the solution is indeed stable.

On the other hand, the stability properties and propagation dynamics of an elliptically polarized discrete surface wave are different as can be seen in Fig. 4. In this example, the TE component carries 108 W, the TM 342 W, and \( \Delta \approx 2.2 \text{ mm}^{-1} \). The eigenvalues of the perturbed problem, in this case, exhibit a complex quartet that can be clearly seen in Fig. 4(c). These complex eigenvalues lead to the growth of perturbations causing the instabilities seen in Figs. 4(a) and 4(b). Here, the TM polarization destabilizes and couples most of its power into the TE polarization. Propagating the beam for a longer distance shows that power is coupled back and forth between the two components with significant radiation into the rest of the array.
4. Experimental Considerations

In experiments, however, some parameters, such as the shape of the beam as well as the relative phase difference between the TE and TM components, can not be precisely controlled. When dealing with highly confined discrete beams, it is most practical to experimentally excite only a single waveguide. However, although stable vector surface wave solutions are highly confined, they do possess a tail that extends throughout the array, but in the experiment this tail will be absent. Moreover, it is difficult to physically launch the two field components exactly in-phase. Therefore, we investigated the effects of these practical concerns on the excitation of vector surface waves. In fact, we found that when only a single waveguide is excited with the appropriate power levels for the TE and TM components (shown in Fig. 2), linearly polarized vector surface waves can propagate in a stable fashion even when the relative phase difference, $\Phi_{TE} - \Phi_{TM}$, is of the order of $\pm 20^\circ$. Of course, this phase mismatch does lead to some power exchange between the TE and TM components via FWM effects. However, this power exchange does not cause the beam to break up. Thus, even if the beam components are not perfectly launched into the array, stable vector surface waves can be observed.

5. Conclusion

In conclusion, we have demonstrated the existence of two-component vector discrete surface waves in Kerr nonlinear AlGaAs waveguide arrays. These mutually trapped states are located in the first waveguide of a semi-infinite array. Stable propagation of a composite beam only occurs when both the TE and TM components are launched into the array in-phase. These solutions also show robustness against practical experimental considerations, thus they are expected to be observed in experiments.