Surface Plasmon Polariton Akhmediev Breather in a dielectric–metal-dielectric multilayer structure

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We report Akhmediev Breather solutions in a nonlinear multilayer structure of subwavelength dimensions. They inherit the properties of Surface plasmon polaritons and its evolution is studied for specific values of nonlinear and dispersion parameters.

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1. INTRODUCTION

Plasmonics, dealing with Surface plasmon polaritons (SPPs), has become a promising area of research over the last few years, due to its ability to break the diffraction limit of light [1, 2]. This has led to numerous experimental and theoretical studies investigating the importance of SPPs. SPPs, being electromagnetic surface modes at a conductor-dielectric interface, enable effective localization of light over subwavelength dimensions and allow efficient control and manipulation of light [3]. Many structures supporting SPP waves have been explored for various applications such as development of optoelectronic devices, sensing, lasing [4, 5] etc. One such structure is the non-linear multilayer structure. The propagation of SPP waves in such a nonlinear structure is governed by the Nonlinear Schrodinger equation (NLSE). The NLSE supports soliton solutions. Surface Plasmon polariton soliton is one of the most promising candidates for the so-called information processing technology based on Plasmonics. One particularly interesting class of solution called Akhmediev Breather has gained tremendous attention recently [6]. These breathers could be exploited to generate ultrashort pulse trains in subpicosecond range, which paves the way to solve many challenging optoelectronic tasks.

In this work, we consider a multilayer waveguide comprising of a metal layer bounded by two semi-infinite dielectric layers. The structure supports SPP wave whose dynamics is governed by the NLSE. We study the Akhmediev Breather evolution for specific values of nonlinear and dispersion parameters. The effect of metal layer thickness in the breather evolution of the structure is also examined.

Figure 1: Multilayer waveguide comprising of a metal layer of thickness ‘h’ bounded by two semi-infinite dielectric layers.
2. MODEL

We consider a model comprising of a dielectric-metal-dielectric multilayer structure in which the metal layer of thickness ‘h’ and a permittivity ‘ε₂’ is bounded by two semi-infinite dielectric layers having permittivity ε₁ and ε₃ respectively. The SPPs supported by the structure propagates along the x direction and z is the normal direction to the layer interface. The media are considered as non-magnetic and the corresponding susceptibilities of the media are assumed to be unity. The metal film is assumed to be made of silver with the dielectric function, ε₂ = ε₁ + ε₆L where ε₆L = ε∞ - (ω_p²/ω²) is the linear part of the dielectric function. ε∞ is the high frequency component, ω_p is the plasma frequency. On the other hand ε₆NL = αI is the nonlinear part of the dielectric function depending on the intensity I. For ε₁ ≠ ε₃, each metal-dielectric interface support SPPs and the dispersion relation governing these SPPs can be derived in a straight forward manner [3].

For a continuous SPP wave having a propagation constant β_o and a carrier frequency ω_o the following wave equation could be obtained [7]:

\[ \frac{\partial A}{\partial t} - i \frac{D}{2} \frac{\partial^2 A}{\partial x^2} + i \gamma |A|^2 A = 0 \] (1)

where A(X, t) is the slowly varying amplitude, γ is the coefficient of nonlinearity at ω = ω_o and D is the group velocity dispersion parameter. Eq. (1) can be rewritten in normalized units as follows:

\[ i \frac{\partial \psi}{\partial \tau} + \frac{1}{2} \frac{\partial^2 \psi}{\partial \xi^2} + |\psi|^2 \psi = 0, \] (2)

In writing Eq. (2) we define a characteristic length L_NL = (γP_o)⁻¹ and a timescale T_o = (|D| L_NL)¹/², such that A=P_o½ψ, X=ξL_NL and t=τT_o [11]. P_o is the input field power.

3. RESULTS AND DISCUSSION

Eq. (2) has the following Akhmedeiv Breather solution [6]:

\[ \psi(\xi, \tau) = \left[ \frac{(1-4a) \cosh(bt) + \sqrt{2} \cos(\Omega t) + i \sinh(bt)}{2 \sqrt{2} \cos(\Omega t) - \cosh(bt)} \right] e^{i \tau}, \] (3)

where Ω is the dimensionless modulation frequency is given by a = 1/2(1 - Ω²/4) and b = [8a(1-2a)]². The evolution of the Breather solution described in Eq.(3) is studied for specific values of nonlinear and dispersion parameters [7].

Figure 2: The evolution of SPP wave in the multilayer structure as a breather solution for h=5 nm for (a) a=0.25, (b) a=0.35, (c) a=0.45 and (d) a=0.49.

Fig. 2 describes the breather evolution of the induced SPP wave for a metal layer of thickness h=5 nm for an input wavelength of λ=450 nm, the power P_o=10⁻² W, the group velocity \( \vartheta_g = 2.5 \times 10^6 \) m/s and the group velocity dispersion...
$D = -2.3 \times 10^{-2} \text{ m}^2/\text{s}$ with the Kerr nonlinearity coefficient $\gamma = 155 \text{ m}^2/\text{W.s}$. On the other hand, Figure 1: The evolution of SPP wave in the multilayer structure as a breather solution for $h=5\text{ nm}$ for (a) $a=0.25$, (b) $a=0.35$, (c) $a=0.45$ and (d) $a=0.49$.

![Figure 1](image1.png)

Figure 3: The evolution of SPP wave in the multilayer structure as a breather solution for $h=10\text{ nm}$ for (a) $a=0.25$, (b) $a=0.35$, (c) $a=0.45$ and (d) $a=0.49$.

![Figure 3](image2.png)

Fig. 3 represents the SPP wave evolution for a metal layer of thickness $h=10\text{ nm}$ with parameter values $P_0=10^{-2}\text{ W}$, $\theta_g = 4 \times 10^5 \text{ m/s}$, $D=-7.9 \times 10^{-3} \text{ m}^2/\text{s}$ and $\gamma=182 \text{ m}^2/\text{W.s}$. For $a<1/2$, the intensity of the pulses is periodic spatially with a repetition rate of few terahertz. However, as $a\to 1/2$ the localization increases spatially with a corresponding increase in temporal localization. The group velocity of the SPP wave is smaller for thicker metal layer. As a result, the SPP wave has a narrower pulse.

4. CONCLUSIONS

We have reported Akhmediev Breather solutions in a multilayer waveguide comprising of a metal layer bounded by two semi-infinite dielectric layers with subwavelength thickness. It is observed that it is possible to obtain stable propagation of the Breather soliton in the structure and with judicious choice of parameters localization of these breathers is achievable which might lead to the generation of extremely short pulses in such multi-layered structure.

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