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Extreme events in complex linear and nonlinear photonic media

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ABSTRACT

Ocean rogue waves (RW) are huge solitary waves that have for long triggered the interest of scientists. The RWs emerge in a complex environment and it is still under investigation if they are due to linear or nonlinear processes. Recent works have demonstrated that RWs appear in various other physical systems such as microwaves, nonlinear crystals, cold atoms, etc. In this work we investigate optical wave propagation in strongly scattering random lattices embedded in the bulk of transparent glasses. In the linear regime we observe the appearance of extreme waves, RW-type, that depend solely on the scattering properties of the medium. Interestingly, the addition of nonlinearity does not modify the RW statistics, while as the nonlinearities are increased multiple-filamentation and intensity clamping destroy the RW statistics. Numerical simulations agree nicely with the experimental findings and altogether prove that optical rogue waves are generated through the linear strong scattering in such complex environments.

1. Introduction

Ocean rogue or freak waves are huge waves that appear in relatively calm seas in a very unpredictable way. Numerous naval disasters leading to ship disappearance under uncertain conditions have been attributed to these waves. Since sailors are well known story makers these monster, destructive waves that were in naval folklore perhaps for thousands of years penetrated the realm of science only recently and after quantitative observations [1,2]. Since then, they seem to spring up in many other fields including optics [3-7], BEC and matter waves, finance, etc [8-12]. Unique features of rogue waves, contrary to other solitary waves, are both their extreme magnitude and also their sudden appearance and disappearance. In this regard they are more similar to transient breather events than solitons. Since the onset of both necessitates the presence of some form of nonlinearity in the equation of motion describing wave propagation, it has been tacitly assumed that extreme waves are due to nonlinearity. Intuitively, one may link the onset of a rogue wave to a resonant interaction of two or three solitary waves that may appear in the medium. However, large amplitude events may also appear in a purely linear regime [1,2,4,6]; a typical example is the generation of caustic surfaces in wave propagation [13,14].

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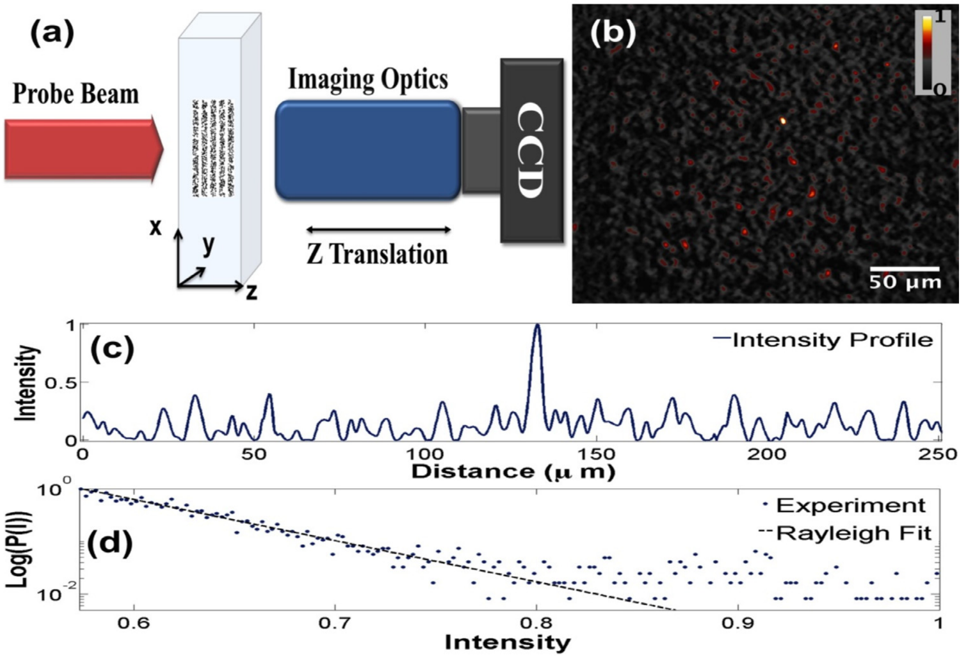

Fig. 1. Experiments: (a) Schematic representation of the experimental setup. A monochromatic coherent plane wave laser beam propagates from the left to right (red arrow) in the glass sample where a five layer random LHs lattice is inscribed. An imaging system allows recording the beam profile at various propagation planes. (b) Experimental observation of an optical rogue wave as it is formed within the LHs lattice (appearing at the 4th layer; almost at the center of the image). The RW is clearly distinct as its intensity is significantly greater from every other wave in the surrounding area in the lattice as seen also at the corresponding intensity profile (c). (d) Intensities distribution (in semilog scaling); rogue waves presence introduces a substantial deviation from the exponential distribution (Rayleigh law) appearing as a tail at high intensities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Propagation of electrons or light in a weakly scattering medium is a well-studied classical problem related to Anderson localization and caustic formation. Recent experiments in the optical regime [15] have shown clearly both the theoretically predicted light localization features as well as the localizing role of (focusing) nonlinearity in the propagation [15-20]. In these experiments a small (of the order of 10^{-3}) random variation of the index of refraction in the propagation leads to eventual localization while at higher powers, where nonlinearity is significant, localization is even stronger. Thus, destructive wave interference due to disorder leads to Anderson localization that may be enhanced by self-focusing nonlinearity. In the purely linear regime propagation in two dimensions in a weakly random medium has shown that branching effects appear through the generation of caustic surfaces [13,14], while linear rogue waves have been observed with microwaves [4].

In this work we focus on an entirely different regime of wave propagation, in strongly scattering optical media that consist of Luneburg-type lenses randomly embedded in the bulk of glasses. Spherical or cylindrical Luneburg lenses (LLs) have very strong focusing properties directing all parallel rays impinging on them to a single spot on the opposite side surface. The index variation is very large, viz. of the order of 40% and thus a medium with a random distribution of Luneburg-type lenses departs strongly from the Anderson regime investigated in [15–20]. In the experimental configuration used in this work we used “Luneburg Holes (LH)” or anti-Luneburg lenses instead of LLs; the LHs have a purely defocusing property. In the methods section we demonstrate that our observations discussed in the following are generic and independent of the type of scatterers.

Experimental and numerical observation of rogue waves. Focusing tightly a femtosecond IR beam into the bulk of fused silica substrates induces nonlinear absorption allowing the selective modification of the material [21]. Under appropriate irradiation conditions one may create LH-type structures and by placing those in a controlled way in space to create three dimensional LH lattices like the ones shown in Fig. 1(a).

The investigation for the presence of a rogue wave is performed by probing a laser beam through the volume of the lattice and imaging the output. This approach is advantageous because it allows the study of both linear and nonlinear phenomena, depending only on the probe beam intensity.

For the linear observations a low power continuous wave 633 nm laser beam was used as probe. A large number of different lattices were studied until “rogue” events were observed as seen in Fig. 1(b). The corresponding “rogue” event intensity profile is shown in Fig. 1(c) and the distribution of the intensities, in semilog scaling, in Fig. 1(d) and permit to conclude that this signal cannot be anything else than an optical rogue wave, contiguous