

Experiments on induced modulational instability of an incoherent optical beam

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We report the observation of modulational instability (MI) of a partially spatially incoherent beam induced by seeding noise through cross-phase modulation. We show experimentally that a threshold exists for such induced incoherent MI to occur that depends on the degree of spatial coherence as well as on the strength of the nonlinearity. Above threshold, the induced MI leads to the formation of ordered and disordered patterns of incoherent light. © 2001 Optical Society of America

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Like solitons, modulational instability (MI) is a universal phenomenon that exists in many nonlinear systems. In optics, solitons form as localized electromagnetic waves when diffraction or dispersion is well balanced by nonlinear self-focusing.¹ Closely related to soliton formation is the process of MI, during which small perturbations in the amplitude or the phase of optical waves grow exponentially as a result of the interplay of nonlinearity and diffraction–dispersion.^{2,3} While MI is a crucial issue for soliton instabilities,^{4,5} it is also considered a precursor to soliton formation because it typically occurs in the same parameter region as that where solitons are observed. In fact, because of MI, a broad optical beam or a quasi-cw pulse often breaks up into filaments that tend to form trains of solitons, as observed in Kerr-like nonlinear media.^{6,7} MI has also been studied in various saturable nonlinear systems such as those that involve photorefractive^{8,9} and quadratic^{10–12} media. However, all these studies were based on coherent light waves. Recently, MI of incoherent light waves was predicted,¹³ following the research on incoherent optical solitons.^{14–16} In contradistinction to coherent MI, incoherent MI occurs only when the value of the nonlinearity exceeds a threshold imposed by the spatial coherence of the beam, which has led to observations of a new class of soliton that cannot be realized in the coherent regime.¹⁷

In this Letter we report experimental observation of induced MI of an incoherent light beam. By actively seeding spatial noise onto a uniform partially spatially incoherent beam through cross-phase modulation, we demonstrate the induced (or driven) incoherent MI in a noninstantaneous nonlinear medium. We provide experimental evidence for the existence of a threshold in such induced incoherent MI, which depends on the degree of spatial coherence of the beam as well as on the strength of the nonlinearity. Above threshold, the MI leads to the formation of ordered and disordered patterns of incoherent light. To our knowledge, this is the first observation of induced transverse instability mediated from incoherent wave packets.¹⁸

In our experiments, a partially spatially incoherent beam is generated by conversion of an argon-ion laser beam ($\lambda = 488$ nm) into a quasi-monochromatic light

source with a rotating diffuser. We vary the spatial coherence of the beam by changing the position of the diffuser and monitor it from the speckle size when the diffuser is set to be stationary. (The speckle size is roughly equal to the spatial coherence length l_c , within which any two points remain phase correlated.) A biased photorefractive crystal (SBN:60; 5 mm \times 5 mm \times 20 mm) is used as the medium that provides noninstantaneous nonlinearity, as the rotating diffuser creates random phase fluctuations on a time scale that is much faster than the response time of the crystal. This noninstantaneous nature of the nonlinearity is essential for incoherent self-trapping and MI.^{13–16} Our experimental setup is similar to that used in earlier experiments with incoherent solitons,^{14–16} except that here we use a broad and uniform extraordinarily polarized incoherent beam for observation of induced MI and a weak gridlike intensity pattern generated from three-beam (all ordinarily polarized) interference as noise. The noise beam is coupled onto the partially incoherent beam at the input face of the crystal. A dc field is applied along the crystalline c axis, which is oriented perpendicularly to the propagation direction of the beams. With this arrangement, the e -polarized incoherent beam dominates the nonlinear index change because for a fixed bias field the strength of the photorefractive nonlinearity is controlled by the intensity and the polarization.^{14–16} The intensity grid seeds spatial noise to the incoherent beam through cross-phase modulation.

First we show that MI occurs to an incoherent optical beam through seeding noise (driven MI) as well as through intrinsic residual noise such as striations and defects in the crystal. Typical experimental results are presented in Fig. 1. With the diffuser stationary, a speckled pattern is seen by the crystal [Fig. 1(a)]. With the diffuser rotating, the partially incoherent beam displays a uniform noninstantaneous intensity pattern [Fig. 1(b)] before we turn on the nonlinearity. When a voltage of 400 V is applied across the 5-mm-wide crystal, the incoherent beam remains fairly uniform [Fig. 1(c)], indicating that no appreciable MI is observed at this level of nonlinearity. We then add the noise beam (with grid spacing

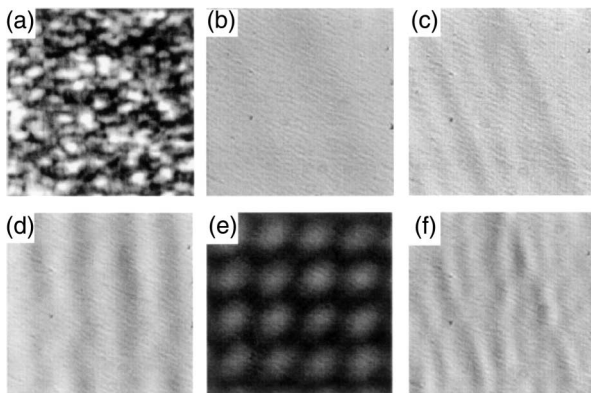


Fig. 1. (a) Speckle pattern taken with the diffuser stationary. (b)–(d), (f) Intensity patterns of a partially incoherent beam at (b) $V = 0$, (c) $V = 400$ without seeding noise, (d) $V = 400$ with seeding noise, and (f) $V = 500$ without seeding noise. (e) Gridlike intensity pattern used for seeding noise (its contrast has been enhanced for clarity).

$\sim 70 \mu\text{m}$ and a peak intensity four times weaker) onto the incoherent beam and keep all other conditions unchanged. After the crystal reaches a new steady state, we observe that the incoherent beam breaks up into one-dimensional (1D) filaments because of the induced MI [Fig. 1(d)]. The index change experienced by the noise beam itself is too weak to cause noticeable self-focusing of the intensity grid [Fig. 1(e)], which remains the same as that at the input. Although the noise is seeded through cross-phase modulation, it is strong enough to induce MI on the incoherent beam. Without seeding noise, however, incoherent MI develops spontaneously and leads to beam breakup only when the applied voltage is increased further [Fig. 1(f)]. Compared with seeding-noise-induced MI, incoherent MI caused by the intrinsic noise is observed on a smaller scale (dominated by striation lines) and at a higher level of nonlinearity. For the experiments of Fig. 1, the average speckle size of the partially incoherent beam is estimated to be $l_c = 25 \mu\text{m}$. The size of the filaments or stripes after beam breakup is much larger than the average speckle size, indicating that the observed phenomenon is attributed to induced incoherent MI.

One major result of the incoherent MI theory¹³ is that, assuming that the incoherent beam takes a Lorentzian-shaped angular power spectrum, MI occurs only when the following condition is satisfied:

$$\kappa I_0/n_0 > \theta_0^2, \quad \kappa = d(\delta n)/dI. \quad (1)$$

κ is the marginal nonlinear index change that is due to constant background intensity I_0 , $\delta n(r)$ is the local index modulation, $I(r)$ is the intensity as a function of coordinate r , and θ_0 is the width of Lorentzian angular power spectra that is related to the degree of spatial coherence of the beam (larger θ_0 corresponds to higher coherence). For the saturable nonlinearity as in photorefractives, the index change obeys the following relation:

$$\delta n \propto \frac{V}{l} \frac{I(r)}{1 + I(r)/I_{\text{sat}}}, \quad (2)$$

where V/l is the bias field and I_{sat} is a constant of saturation intensity. Expressions (1) and (2) indicate clearly that incoherent MI occurs when the nonlinearity (controlled through either the beam intensity or the bias field) exceeds a threshold value imposed by the degree of beam coherence.

We perform the following experiments on induced incoherent MI for qualitative comparison: To avoid the anisotropic effect of photorefractive self-focusing nonlinearity,^{8,9} which tends to break up the beam first into vertical stripes, we turn the intensity grid into a diagonal pattern (i.e., the intensity fringes are oriented diagonally rather than vertically or horizontally). We find that induced incoherent MI occurs only when the degree of spatial coherence reaches a threshold value if the strength of the nonlinearity is kept constant. Above threshold, the incoherent beam tends to break up into filaments that form ordered and disordered patterns. Figure 2 shows the development of induced MI on the incoherent beam as the beam's spatial coherence is increased gradually. When the speckle size is small ($l_c = 10 \mu\text{m}$), the incoherent beam remains uniform, even with a voltage of 500 V applied [Fig. 2(a)], indicating that the nonlinearity is below the threshold. As we increase the speckle size to $l_c = 20 \mu\text{m}$ with all other conditions unchanged, we observe the breakup of the incoherent beam into 1D stripes [Fig. 2(b)]. Further increasing the speckle size leads to breakup of the stripes into ordered two-dimensional filaments [Fig. 2(c)]. Far above the threshold value, the partially incoherent beam forms a disordered pattern [Fig. 2(d)]. Because the filaments are now formed at smaller sizes than are the speckles, the disordered pattern is attributed partly to coherent MI that results from intrinsic noise. We note that the same intensity grid is used for driving the patterns in Fig. 2. The preferred direction in the formation of periodicity may result from the slightly higher fringe intensity of the seeding beam in this direction than of that in the other diagonal direction.

Finally, at a fixed degree of spatial coherence of the beam, we find that the threshold for induced incoherent MI depends on the strength of the nonlinearity, which is controlled by the bias field when the beam intensity is kept constant. As the applied voltage is increased gradually, we observe a similar sequence of

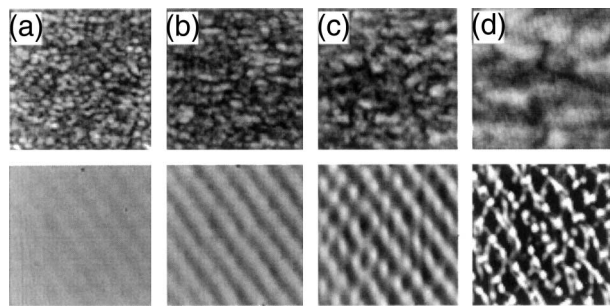


Fig. 2. Development of induced incoherent MI as the spatial coherence of the beam is increased gradually: (a) $l_c = 10 \mu\text{m}$, (b) $l_c = 20 \mu\text{m}$, (c) $l_c = 30 \mu\text{m}$, and (d) $l_c = 60 \mu\text{m}$. Top, the speckle patterns with the diffuser stationary. Bottom, the corresponding intensity patterns at $V = 500$ with the diffuser rotating.

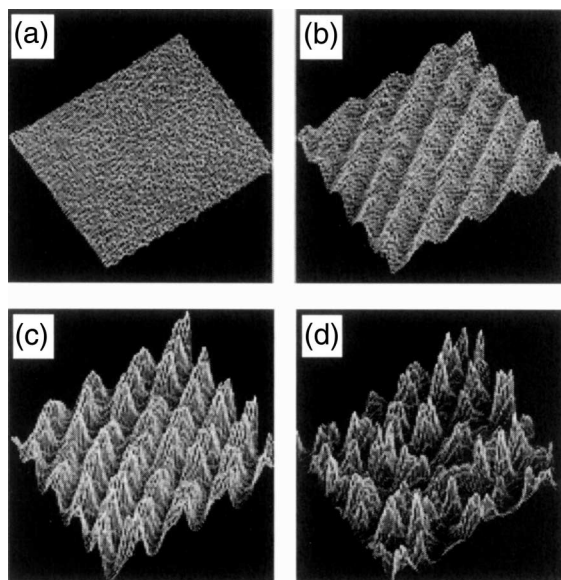


Fig. 3. Development of induced incoherent MI as the strength of the nonlinearity is increased gradually. Shown are intensity patterns at $l_c = 20 \mu\text{m}$ for (a) $V = 200$, (b) $V = 500$, (c) $V = 800$, and (d) $V = 1400$.

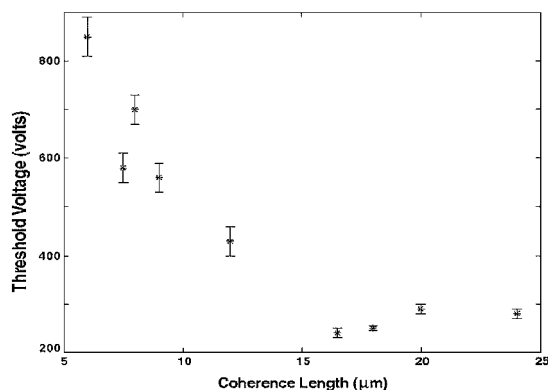


Fig. 4. Measured threshold values of externally applied voltage as a function of coherence length.

pattern formation. Figure 3 shows the three-dimensional intensity patterns of the incoherent beam for various values of the bias field when the speckle size of the incoherent beam is kept at $l_c = 20 \mu\text{m}$. When the nonlinearity is low ($V = 200 \text{ V}$), the incoherent beam remains uniform [Fig. 3(a)]. At a threshold value of $V = V_{\text{th}} = 500 \text{ V}$, induced incoherent MI occurs and leads to breakup of the beam into 1D stripes [Fig. 3(b)]. As the voltage is further increased, MI causes the beam to break up in two dimensions and to form structures akin to arrays of solitons [Fig. 3(c)]. Well above threshold ($V = 1400 \text{ V}$), the breakup results in disordered patterns [Fig. 3(d)]. Furthermore, in another set of experiments, we measure V_{th} as a function of beam coherence l_c while keeping the beam intensity constant. As the coherence is increased, V_{th} decreases. A series of experimental data is plotted in Fig. 4. One could perform similar experiments to measure the threshold intensity while keeping the applied voltage constant. We point out that a few

points in Fig. 4 did not go exponentially, and there are large experimental uncertainties in determining V_{th} (one would expect that V_{th} should reach zero as l_c goes to infinity, i.e., no threshold exists for coherent MI.) Our experiments are in qualitative agreement with predictions from 1D theory.¹³

Before closing, we emphasize the difference between coherent MI and incoherent MI. Unlike coherent MI, incoherent MI occurs at a threshold value of nonlinearity imposed by the coherence, and it grows at a lower rate. Furthermore, the filaments formed after the beam breakup as a result of incoherent MI have no or only weak phase correlation, so the force between them is weakly attractive (as two mutually incoherent solitons always attract). Because of this feature, the filaments from breakup of an incoherent beam tend to form soliton clusters or to fuse together into trains of large-sized solitons at exceedingly high nonlinearity [Fig. 3(d)], unlike for coherent MI, in which the filaments experience mainly repulsive force.

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