Passive transverse-mode organization in a photorefractive oscillator with saturable absorber

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We present and demonstrate a self-transverse-mode organization effect (passive transverse mode locking?) in a cavity that contains a saturable absorber. It gives narrowing and filamentation of the oscillating beam in the region of the absorber. In the demonstration, we have used a resonator formed by two photorefractive phase conjugate mirrors. The saturable absorber was bacteriorhodopsin in a polymer film. Light powers of 1–100 mW were used.

Passive mode locking of lasers[1–3] has been known for almost 25 years and is still an important way for generating short light pulses. It is based on the insertion of a saturable absorber (SA) into the laser cavity. The SA encourages oscillation in short pulses, where the light intensity is large and the loss in the absorber is minimized. In this process, many longitudinal modes are locked together. We could consider, however, another way for obtaining energy compression by using the transverse dimension of the oscillating beam in the cavity rather than the longitudinal one. In this case, transverse mode locking would give a reduced cross section with high power density, resulting in continuous oscillation with low loss in the SA. This scenario is, however, problematic and was not considered in the past since it requires the oscillator to support a very large number of transverse modes with low losses. The superposition of these modes with the right phase relations could have provided the reduced cross section of the beam.

In this letter we show that such self-transverse-mode organization (or locking) of an oscillating beam is obtainable. In the demonstration, we used a special resonator formed by two photorefractive phase conjugate mirrors.[4–6] Such a phase conjugate resonator can support a large number of transverse modes. The SA was a film of bacteriorhodopsin[7,8] in a polymer matrix. Its low saturation intensity of (10–100) mW/cm^2 is compatible with typical beam intensities used in photorefractive oscillators.[5]

The oscillation was formed between two facing double phase conjugate mirrors[4–6] (DPCMs), as is schematically shown in Fig. 1. Each DPCM consisted of a photorefractive $BaTiO_3$ crystal pumped by a single beam from the 514.5 nm line of an argon ion laser. The DPCM is based on four-wave mixing and self-induced gratings that produce two phase conjugate beams. As in other photorefractive devices, the steady-state behavior of the oscillator does not depend on the absolute intensities of the input beams but only on intensity ratios[3,4] (and on the coupling strength of the crystals). We have shown in the past that such a resonator can support oscillation of beams with complex pictorial information. This flexibility and intensity independence provide the basic requirement for the demonstration below.

The SA in our experiment was made of a bacteriorhodopsin in a polymer (polyvinylalcohol) matrix.[7] Bacteriorhodopsin is contained in the purple membrane of the bacterium *Halobacterium halobium* and has a strong nonlinear and saturation response. Films with a thickness of $\sim 100\ \mu$m and an area of few cm^2 were prepared. We have used them recently in wave mixing experiments and studied their nonlinear behavior.[7] Their typical saturation intensities of (10–100) mW/cm^2 make them suitable for use at the low power densities typical in photorefractive wave mixing experiments. The transmissivity of the SA films increases from $\sim 50\%$ for signal intensities of ~ 1 mW/cm^2 to $\sim 80\%$ for ~ 200 mW/cm^2.

To begin the experiment, we obtained oscillation between the two photorefractive crystals (M_1 and M_2 in Fig. 1) without the SA. The pump beams P_1 and P_2 were slightly focused into the crystals by lenses with focal lengths of 100 mm. The effective size of each nonlinear mirror, given by the shape of the pump beams, was ~ 0.5 mm in the vertical direction and ~ 2 mm in the horizontal direction. (The values are slightly different for the two mirrors.) This is approximately the projection of the pumps' pattern in the crystals on the oscillation cross section. P_1 and P_2 were mutually incoherent and had almost the same power for optimum operation.[5] The pumps' power ratio was held constant in our experiment, keeping unchanged also the oscillation to pumps power ratios. We also inserted into the cavity two lenses with focal lengths of 50 mm, each of them ~ 50 mm from one of the crystals, in order to exploit the broad angular bandwidth of the gain. When no oscillation takes place, this gain causes amplifi-

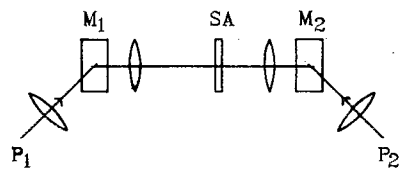

FIG. 1. Scheme of the resonator, formed by two facing double-phase conjugate mirrors M_1 and M_2 and pumped by beams P_1 and P_2. SA is the saturable absorber.

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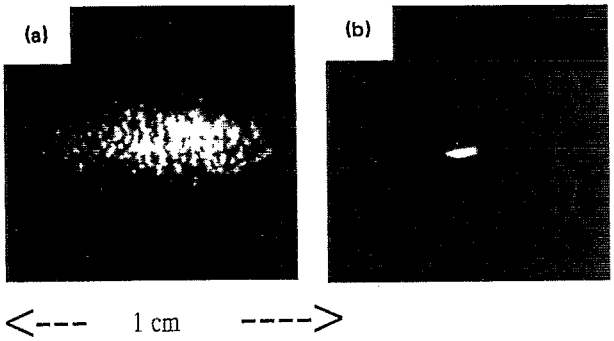
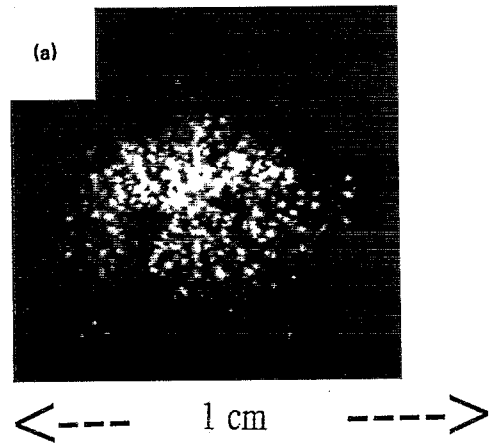


FIG. 2. Cross sections of the oscillating beam without the SA inside the cavity: (a) at the (vacant) location of the SA, (b) at the location of the mirror M_1.

cation of noise in that wide angular range (the fanning effect), which is analogous to the amplified spontaneous emission and its broad frequency bandwidth in laser media.

After oscillation had built up between the nonlinear mirrors, the beam in the cavity had a narrowed angular width compared to the former fanning. The beam between the two lenses was quasicollimated with inhomogeneous cross section of (20–30) mm^2, as shown in Fig. 2(a). This relatively wide cross section is built up from many amplified noise components and has a complex wavefront. This is the "transverse nonlocked" (or "transverse cw") oscillation, which is analogous to the "cw" oscillation of lasers in the time domain. The picture in Fig. 2(a) shows the cross section at approximately the middle of the cavity, where the SA is placed in the next experiment. The cross sections near the mirrors, which had an oval shape, were much smoother [as shown in Fig. 2(b)], for optimized use of the uniform gain volume, circumscribed by the pumps in the photorefractive crystals. We also obtained good phase conjugate beams of the pumps P_1 and P_2, which are a part of the oscillation. No significant change of the oscillation structure was observed when we simultaneously varied the power of the two pumps (using a variable beam attenuator before splitting the laser beam for the two pumps) between $\sim$0.1 mW to a few hundreds of mW. Only the oscillation power varied accordingly.

Now we turn to the effect of inserting the SA into the cavity. Since the steady-state structure of the photorefractive oscillation (without the SA) does not depend on the absolute intensities of the pump beams, we were free to adjust its intensity level according to the SA response. At high intensities compared to the saturation of the absorber, the oscillating beam maintained a broad cross section [shown in Fig. 3(a)] similar to the case without the SA. However, when the power was lowered [to $\sim$(2–3) mW in a typical experiment], the cross section of the oscillating beam near the location of the SA collapsed into few small areas (filaments), as shown in Figs. 3(b) and 3(c). The cross section near the mirrors remained uniform as in Fig. 2(b). At the SA, we generally obtained several dots and sometimes lines (mainly in the vertical direction). Further reduction of the power caused a further decrease of the area and the number of filaments in the SA region [Fig.



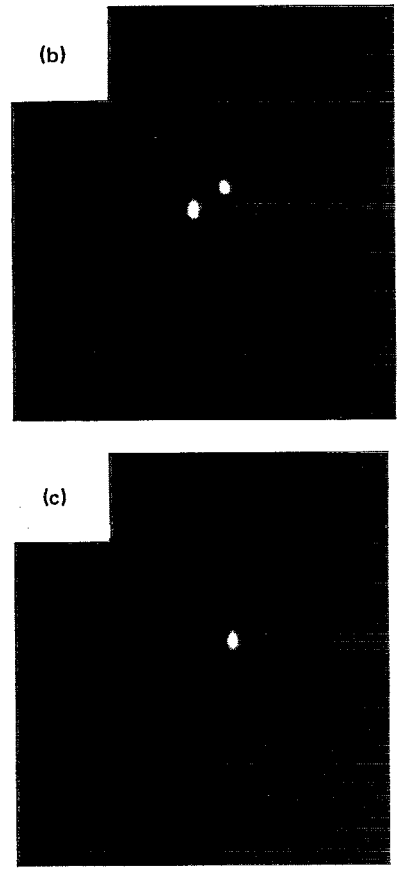


FIG. 3. Cross sections of the oscillating beam at the SA plane with the saturable absorber (SA) placed inside the cavity (a) for the nonlocked case (high oscillation power), (b) for the locked case with low oscillation power, (c) for the locked case with further lowering the oscillation power.

3(c)]. The diffraction limit for the spot size at the SA is determined by the angular bandwidth of the photorefractive gain,[9] which is 10^0–20^0 in the horizontal dimension and about half of this value for the vertical dimension and the effective sizes of the nonlinear mirrors. This gives minimum sizes of $\sim$1 and 2 μm for the two dimensions. The total power through the shrunken cross section in the SA plane was roughly equal to that in the wide uniform cross section (cw) obtained without the SA. This strong dependence of the oscillation structure on beam intensity was the

key difference in behavior exhibited by the oscillator with SA, as against the behavior without SA.

When we started to increase the pump power into the oscillator (with SA) from zero, a certain power was needed to initiate oscillation (typically 3–4 mW for each pump beam in our experiment.) However, after the oscillating beam had burned its way through the SA, it was possible to lower the power (to $\sim$1 mW) for each of the two pumps and maintain oscillation. Lowering the pump power caused a compression of the oscillation power into a smaller cross section and fewer filaments, such that the power density at the SA remained approximately unchanged. This kept the power densities high enough to make the SA transparent. The time response of the system is determined by the time constant of the photorefractive crystal and varies between seconds and a few minutes depending on the light intensity range of the experiment.[5] The time response of the bacteriorhodopsin film is on the order of *milliseconds*.[7]

One can interpret the self-organization process as self-locking of many transverse modes in the cavity (with a degenerate frequency), such that their superposition gives the collapsed cross section. Since our resonator was capable of supporting oscillating beams with almost arbitrary cross sections, the meaning of and the way to identify here individual transverse eigenmodes (Gaussian modes) can be problematic and debatable. Nevertheless, transverse modes were observed[10] in a photorefractive ring oscillator, where a pinhole was added to the cavity. In our experiment, however, we preferred to have a wide cross section, which is a kind of transverse cw oscillation (without the SA), built up from many amplified noise components that give a complex wavefront. The locked oscillation with the SA enhanced the buildup of noise components of which superposition provided a beam with the small cross section near the SA. It was possible by the nonlinear mirrors (the DPCMs), which could form the needed wavefronts by their dynamic volume holograms. In this picture, the effect can be viewed as a transverse mode analog to the formation of pulses in a (passive) longitudinal mode-locked laser. An "active" aperturing is also possible in our experiment, resulting in an oscillation which exactly fits its cross section to the reduced shape of the aperture[11,12] (but is not further reduced as occurs in active longitudinal mode locking, where the pulses are shortened.) A different point of view of mode suppression can be considered, especially in the case where the SA is located at the Fourier plane of the mirrors. The cw oscillation with the wide cross section at the SA (Fourier) plane is a sum of many plane wave components with slightly different directions in the mirrors plane. It is essentially a discrete sum, as seen by the dots at the SA plane [Fig. 3(a)]. The effect of the SA is to suppress most of these components.

In conclusion, we have presented and demonstrated a self-transverse-mode organization effect. We have used a special oscillator with two photorefractive mirrors (DPCMs) and a saturable absorber which was derived from bacteriorhodopsin. We are continuing to investigate other aspects of this system, such as optically induced images on the intracavity SA.

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