# Formation of Repetitively Nanosecond Spatial Solitons in a Saturable Absorber $Q$-Switched Laser

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We report on an experimental observation of repetitively nanosecond spatial solitons in a saturable absorber $Q$-switched microchip laser. The formation of high-peak-power spatial localized structures is achieved by controlling the self-focusing effect in a nearly hemispherical resonator. Our experimental results not only show qualitative agreement with theoretical predictions but also give quantitative criteria for the self-focusing nonlinearity. In addition, we also observe the coexistence of amplitude and phase solitons.

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Pattern formation [1] in optical systems [2] includes two kinds of localized structures: optical vortex [3] and spatial solitons [4]. Spatial solitons excited in optical resonators are generally known as cavity solitons, which have attracted significant attention in recent years [5]. According to the intensity distribution, cavity solitons can be classified into phase and amplitude spatial solitons [6–8], which are usually referred to as dark rings and bright spots, respectively. Numerical investigation has revealed that amplitude and phase solitons can coexist in the same optical system with a subcritical pitchfork bifurcation [9].

With the Maxwell-Bloch equation system, it is found that subcritical nonlinear resonators such as lasers with intracavity saturable absorbers can be described by a modified Swift-Hohenberg equation and can support bright spatial solitons [9]. On the other hand, from the point of view of temporal dynamics, a saturable absorber in a laser cavity can be used to produce repetitively short pulses from nanosecond ($Q$-switching) to femtosecond (mode-locking) regimes [10]. Even though cavity solitons have been experimentally observed in a laser with a saturable absorber [8,11], there have been no experiments so far, to our knowledge, demonstrating spatial solitons in a passively $Q$-switched or mode-locked laser. Cavity solitons are attracting considerable attention due to their promising applications in optical information processing and storage [12,13]. An external control beam is usually needed to manipulate solitons for the realization of such applications. In a passively $Q$-switched or mode-locked laser, however, it is not necessary to use an additional control beam because the manipulation of cavity solitons can be achieved directly by modulating the pump source. Furthermore, the signal-to-noise ratio can be considerably enhanced in a repetitively high-peak-power pulsed laser. Certainly, it would be highly desirable to generate spatial solitons in a passively $Q$-switched or mode-locked laser.

In this Letter we experimentally demonstrate the formation of repetitively nanosecond spatial solitons in a saturable absorber $Q$-switched microchip laser. Experimental results reveal that controlling the focusing spot size on the saturable absorber can lead to a transition of the spatial localized structures from amplitude-dominant domains to phase-dominant solitons. We also observe that amplitude and phase solitons can coexist in a saturable absorber $Q$-switched laser.

The setup of our experiment is a passively $Q$-switched microchip $Nd:YVO_4$ laser with a $Cr^{4+}$:YAG crystal as a saturable absorber, as shown in Fig. 1. The subtle balance between the naturally occurring diffraction and the material-induced self-focusing plays a vital role in the formation of stable spatial solitons. To achieve the required focusing nonlinearity, a saturable absorber $Cr^{4+}$:YAG was coated as an output coupler in a nearly hemispherical cavity. The active medium was an $a$-cut 2.0 at.% $Nd^{3+}$, 1-mm-long $Nd:YVO_4$ crystal. The tight focusing in the saturable absorber $Cr^{4+}$:YAG supplies the required nonlinearity. Furthermore, this tight focusing

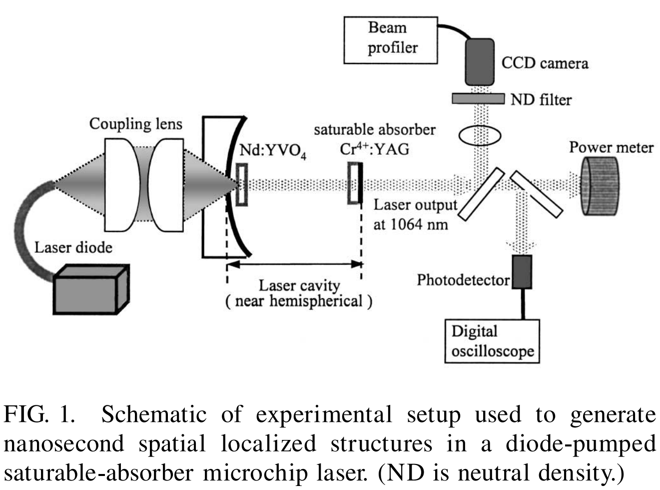


FIG. 1. Schematic of experimental setup used to generate nanosecond spatial localized structures in a diode-pumped saturable-absorber microchip laser. (ND is neutral density.)

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also enhances the performance of passive $Q$ switching because the Nd:$YVO_4$ crystal has a very large stimulated emission cross section. The pump source was a 1-W, 808-nm fiber-coupled laser diode with a core diameter of 100 $\mu$m and a numerical aperture of 0.2. Both sides of the laser crystal were coated for antireflection at 1064 nm ($R < 0.2\%$). Focusing lens with 12.5 mm focal length and 92% coupling efficiency was used to reimage the pump beam into the laser crystal. The pump spot radius $w_p$ was around 25 $\mu$m. The spherical mirror $M1$ was a concave mirror with antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), high-reflection coating at lasing wavelength ($R > 99.8\%$), and high-transmission coating at the diode wavelength on the other surface ($T > 95\%$). The radius of curvature of the spherical mirror, $R_c$, is 15 mm. Note that the laser crystal was placed very near the input mirror. The $Cr^{4+}$:YAG crystal has a thickness of 0.7 mm with 96% initial transmission at 1064 nm. One side of the $Cr^{4+}$:YAG crystal was coated so that it was nominally partially reflecting at 1064 nm ($R = 98\%$). The remaining side was antireflection coated at 1064 nm. With a precise microstage, the position of the saturable absorber was adjustable to change the effective cavity length $L$ in the range of 14.5–15.0 mm.

The present resonator with near-hemispherical configuration has a very small spot size on the saturable absorber given by $w_0 = \sqrt{(\lambda L/\pi)\sqrt{\Delta L/L}}$ and a very large spot size on the laser crystal given by $w_l = \sqrt{(\lambda L/\pi)\sqrt{L/\Delta L}}$, where $\lambda$ is laser wavelength, $\Delta L = R_c - L$, and $\Delta L \ll L$ [10]. The point of exact equality ($\Delta L = 0$) is actually a singularity and unstable. However, a cavity slightly shorter than the exact hemispherical configuration is quite stable. By making small adjustments in the cavity length, the spot size $w_0$ on the saturable absorber can be made as tiny as desired, whereas the spot size $w_l$ on the laser crystal becomes correspondingly large. Since the mode-to-pump size ratio $w_l/w_p \gg 1$, the present resonator can support only pure $TEM_{00}$ Gaussian mode without any self-focusing nonlinearity. In contrast, the effect of self-focusing nonlinearity can give rise to the formation of spatial localized structures in the present configuration. Therefore, the influence of self-focusing nonlinearity on the formation of transverse patterns can be manifestly distinguished and can be easily manipulated by very slight variations in $\Delta L$.

With varying $\Delta L$ from 1 to 400 $\mu$m, the average output power was found to increase gradually from 3 to 110 mW, except for a power dip at $\Delta L \approx 100$ $\mu$m. We have observed 11 distinct types of pattern during the variation of cavity length, as shown in Fig. 2. The experimental patterns were measured using a charged-coupled device (CCD). All observed patterns are remarkably stable and repeatable and show no variation in structure over time scales of hours except for pattern (a). Pattern (a) shown in Fig. 2 is intermittently stable because of approaching the

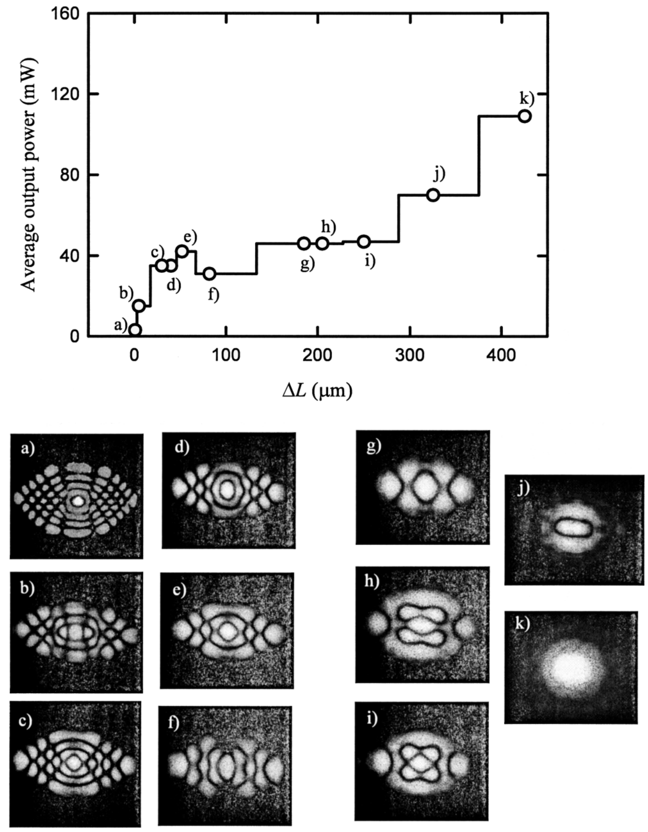


FIG. 2. Upper plot: dependence of the average output power at 1064 nm on the variation of cavity length $\Delta L$. Lower plot: the observed transverse patterns during the variation on cavity length; the cavity length for the patterns (a)–(k) are one-to-one labeled in the upper plot.

unstable boundary. Slowly and gradually varying the cavity length, the transition between two different patterns is found to be abrupt and sudden. Moreover, all observed patterns are found to be preserved in free-space propagation.

Patterns (a)–(e) in Fig. 2, corresponding to $1 < \Delta L < 50$ $\mu$m, display regular ensembles of amplitude solitons. This result is consistent with the theoretical prediction [11] that lasers with intracavity saturable absorbers may constitute subcritical nonlinear resonators, which can support stable bright spatial solitons. In addition, the present observation manifestly indicates that the number of amplitude solitons strongly depends on the spot size $w_0$ on the saturable absorber. The smaller the spot size $w_0$, the larger the self-focusing nonlinearity in the resonator. The beam spot sizes on the absorber $w_0$ for patterns (a)–(e) in Fig. 2 are measured 6, 10, 15, 16, and 17 $\mu$m, respectively. In our experiment it is found that the critical value of $w_0$ for the ensemble formation of amplitude solitons is approximately 17–18 $\mu$m.

When the spot size $w_0$ increases up to 19 $\mu$m, corresponding to pattern (f) in Fig. 2, the localized structures are transformed into bright stripes. The dip of the output power at pattern (f) seems to indicate a transition between different pattern formations. As shown in patterns (g)–(j) of Fig. 2, when the spot size $w_0$ is within 20–27 $\mu$m, corresponding to $100 < \Delta L < 320$ $\mu$m, the transverse pattern displays different types of localized structures, appearing as dark rings (phase solitons). From the viewpoint of the required spot size on the saturable absorber, the dark rings are much easier to excite than the bright solitons in subcritical systems. Indeed, patterns (a), (c), (d), and (e) in Fig. 2 exhibit a dark ring around the central beam. This phenomenon confirms the possibility that amplitude and phase solitons can coexist in the same optical system. Finally, when the spot size $w_0$ exceeds 29 $\mu$m, corresponding to $\Delta L \approx 420$ $\mu$m, the transverse pattern becomes $TEM_{00}$ Gaussian distribution, as depicted in pattern (k) of Fig. 2. This result indicates that the spot size $w_0$ on the saturable absorber needs to be considerably less than 29 $\mu$m for the formation of spatial localized structures.

In addition to spatially localized structures, the temporal behavior of the output laser is a standard high-repetition-rate passively $Q$-switched pulse. The pulse temporal behavior was recorded by a LeCroy 9362 digital oscilloscope (500 MHz bandwidth) with a fast silicon photodiode. The pulse repetition rate is found to be generally proportional to the average output power, as depicted in Fig. 3. In other words, the pulse energy is nearly insensitive to the localized structure and is estimated to be approximately $0.8 \pm 0.1$ $\mu$J. The pulse width is also found to be nearly independent of the transverse pattern and is measured to be around 20 ns. A typical oscilloscope trace of a train of pulses is shown in Fig. 4. The pulse-to-pulse amplitude fluctuation was found to be within $\pm 5\%$. On the whole, the peak output power ($\sim$40 W) is 40 times higher than the average pump power ($\sim$1 W). To our knowledge, this is the first time that a repetitively nanosecond laser with spatial localized structure has been demonstrated.

In conclusion, we have realized repetitively nanosecond spatial solitons in a saturable absorber $Q$-switched microchip laser. A saturable absorber is coated as an output coupler in a nearly hemispherical resonator to control the self-focusing nonlinearity and to enhance the performance of passive $Q$ switching. In a large self-focusing nonlinearity, the observation of bright spatial solitons is in good agreement with the theoretical prediction. On the other hand, the required self-focusing effect is found to be considerably smaller for the generation of phase solitons than for the formation of bright solitons. Finally, the possibility for the coexistence of phase and amplitude solitons is also confirmed in the present experiment.

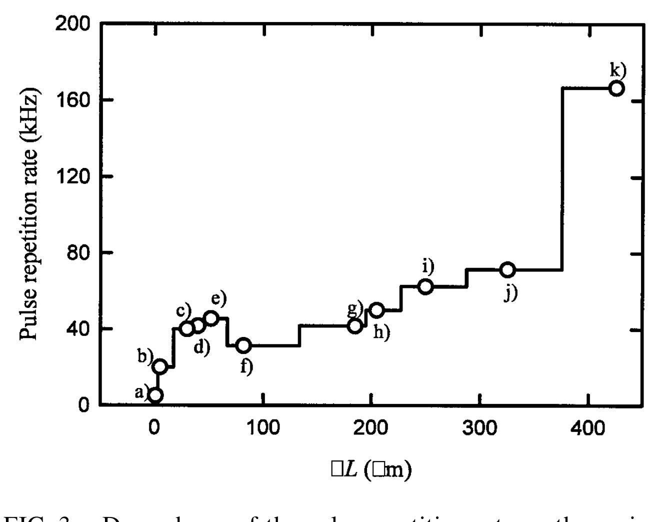


FIG. 3. Dependence of the pulse repetition rate on the variation of cavity length $\Delta L$. The observed transverse patterns are shown in Fig. 2.

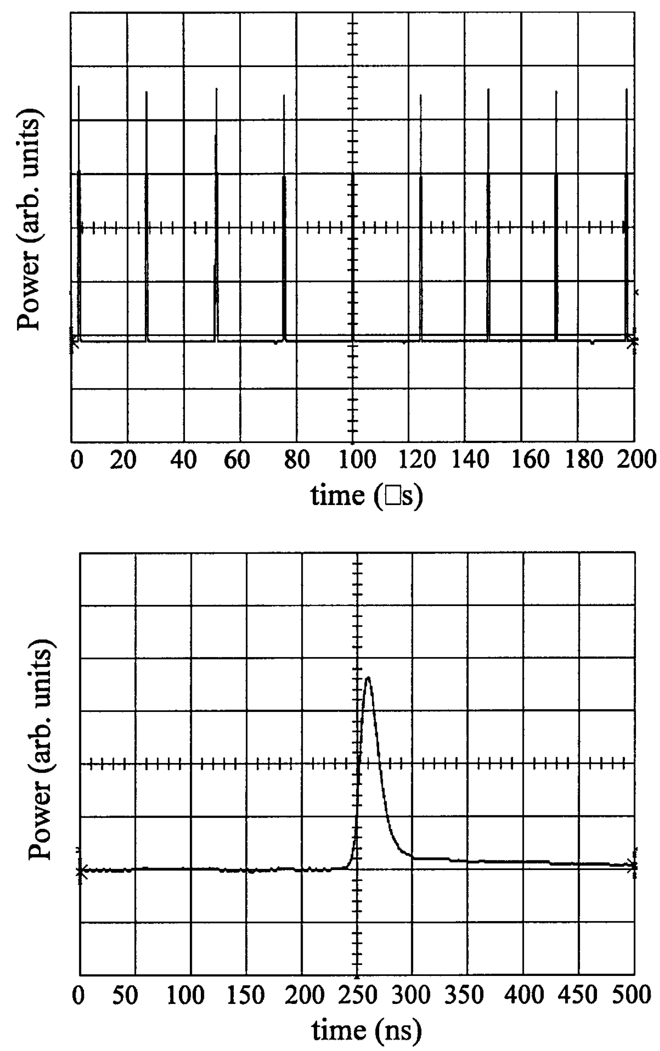


FIG. 4. Oscilloscope traces of a train of pulses from the $Q$-switched spatial soliton laser. Lower trace is an expanded shape of a single pulse.

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