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Phase locking of short-pulse Q-switched lasers

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ABSTRACT

The effects of frequency mismatch on phase locking of two passively Q-switched lasers have been studied. Stable phase locking with a high degree of spatial coherence can be obtained for frequency mismatches that are less than the spectral linewidth of the laser pulses. As the frequency mismatch increases, the transition from the phase locked to the unlocked states is characterized by a gradual loss of coincidence of the pulses from the individual elements and a reduction in the fringe contrast in the combined laser beam. An explanation for observed phenomena based on the dynamics of the transverse modes of the laser array is provided.

1. Introduction

There has been much interest in the techniques that will permit phase locking of a number of lasers to produce a coherent beam. Various schemes, such as employing the evanescent coupling [1–3], an intra-cavity spatial filter [4–7], an intra-cavity interferometer combiner [8], and the Talbot effect [9] have been studied. Most of the studies have concentrated on phase locking of the continuous-wave or long pulsed lasers with multiple gain elements. For the continuous-wave lasers, the phase-locked state is characterized by a time-independent interference fringe pattern in the far field where the laser beams from the individual elements overlap. To maintain a stable interference fringe pattern, all the elements in the phase-locked laser array must operate at the same frequency even though the optical path lengths of the individual elements might be different. Thus the operating frequencies of the phase-locked modes of the laser array are not necessarily the frequencies of the individual lasers when they are uncoupled. As the coupling among the elements decreases or the frequency mismatch increases, the phase-locked state cannot be maintained and the transition from the phase-locked to the unlocked states is signified by an abrupt occurrence of multiple frequencies of the individual lasers [2]. In short-pulse lasers, however, the conditions for phase locking differ from those of the continuous-wave lasers in two ways. Firstly, two or more pulsed lasers operating at slightly different frequencies may produce a stable interference fringe as long as the fringe movement caused by the beat waves is smaller than the fringe spacing during the pulse. Using a two-element pulsed laser array as an example, the maximum frequency mismatch to allow a temporally stable fringe pattern is determined by the rate at which the beat waves sweep through half the fringe spacing or $1/(2\tau)$, where τ is the duration of the pulses. For Q-switched lasers emitting nanosecond pulses, the upper limit of frequency mismatch among the elements in a laser array is on the order of 100 MHz. Secondly, the pulses generated by the individual elements operating at slightly different frequencies may not emerge simultaneously. This can lead to pulse distortion and the loss of spatial coherence in the combined output when the system is operated near the boundary of the phase-locked and unlocked states. To date, few studies have been done on the behavior of phase-locked pulsed lasers.

In this paper, we report a study of the effect of frequency match on phase locking of two Q-switched lasers. The study is done in a system of two passively Q-switched Cr, Nd:YAG microchip lasers created on a single crystal [10]. In this monolithic system, the key parameters that affect the coupling between the lasers, such as the frequency mismatch and coupling strength, can be accurately controlled. A low-Q external resonator is used to facilitate the coupling without causing appreciable pulse broadening. We have found that, when the frequency mismatch between the laser elements is nearly zero, the two lasers can be phase locked with a high degree of spatial coherence while maintaining the optical quality and short-pulse duration. As the frequency mismatch increases, the transition from the phase-locked state to the unlocked state is characterized by a gradual loss of coincidence of the pulses accompanied by a reduction in the fringe contrast. When the frequency mismatch is much larger than the spectral linewidth, the phase-locked pulses can be widely separated in time, by as much as ten times the pulse duration, with no measurable relative timing jitter. The observed phenomena can be explained based on the dynamics of the transverse modes in the two-element laser array of unequal length.

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2. Experimental

The schematic of the coupled laser system is shown in Fig. 1. The Q-switched lasers are formed in a 2-mm-thick Cr, Nd:YAG crystal in which the Cr^{4+} ions act as the saturable absorbers [10]. The neodymium concentration is 1.1-wt%. The unsaturated absorption coefficient caused by the saturable absorber is 0.21 cm^{-1} at 1064 nm. The laser crystal is polished to form a flat–flat Fabry–Perot cavity. The pump facet is coated for high transmission at 808 nm and high reflection at 1064 nm. The output facet is coated for 97% reflectivity at 1064 nm and high reflection at 808 nm to allow double passes of the pump beams within the gain medium. The lasers are end-pumped by diode laser beams through two optical fibers, each delivering 1.5 W at 808 nm. The pumping diodes are operated in the quasi-CW mode with a 300-μs pulse duration and at a repetition rate of 100 Hz. The diameter of the pumped region is approximately 200 μm. The maximum output pulse energy is 10 μJ per element. The center-to-center separation between these two fibers is chosen to be 500 μm. At this separation, the far-field pattern when the two lasers are operating simultaneously is identical to those of the individual elements, indicating that the coupling between the lasers through the evanescent waves is negligible. The lasers are coupled to a Fourier-transform resonator which allows the relative phase of the laser elements to be stabilized by controlling the far-field pattern at the output mirror [6,7]. The output facet of the laser crystal is placed at one focal plane S1 of the converging lens and the output mirror is placed at the other focal plane S2. The focal length of the lens is 10 cm. A 1 cm thick etalon with a finesse of 60 at the lasing wavelength is used to analyze the lasing spectra. The beam profiles at the output mirror at S2 and the interference fringes after the etalon are monitored by two charge-coupled-device cameras. Three fast photodiodes are used to detect the output of the individual elements and the combined output.

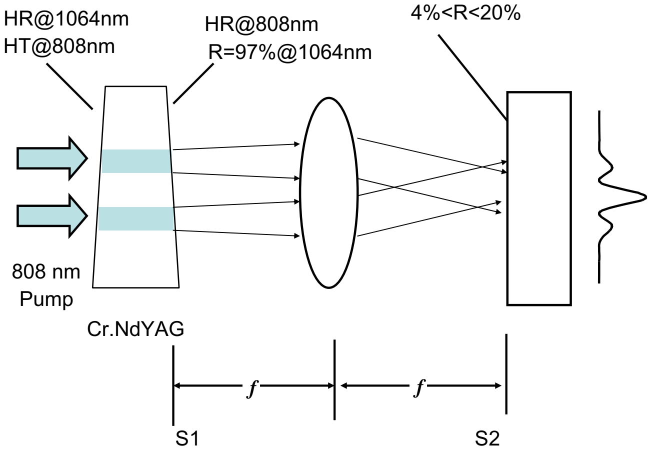

Fig. 1. Schematic of the coupled Q-switched lasers.

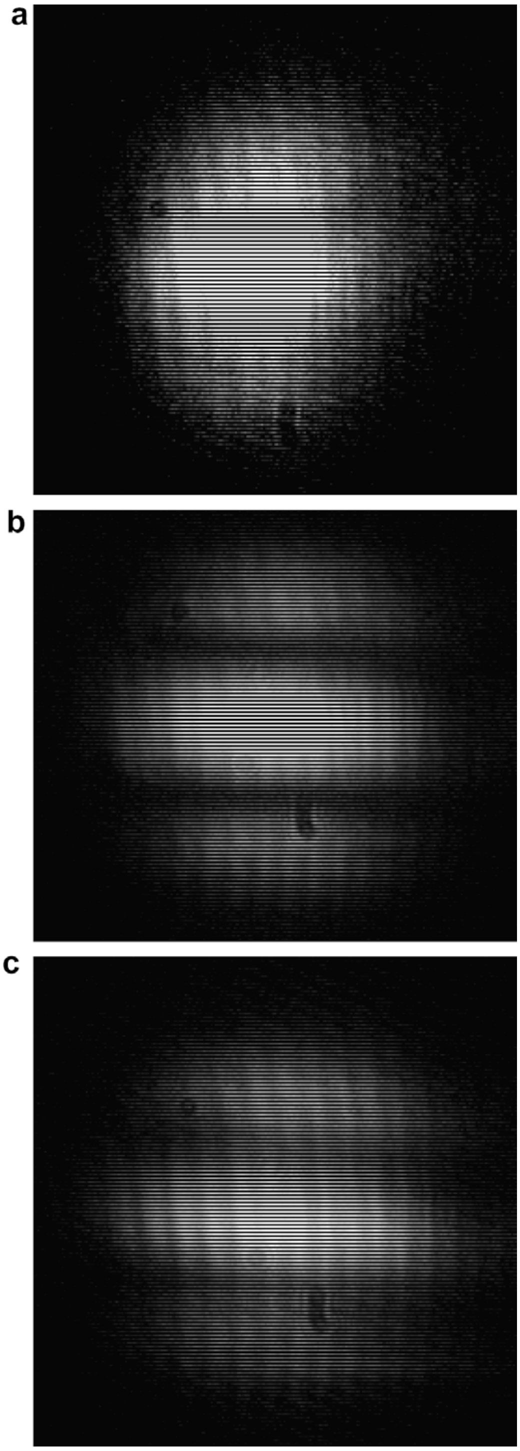

Fig. 2. Beam patterns of the two lasers operating (a) in the free-running state without the external resonator, (b) in the phase-locked state with zero frequency mismatch and (c) phase locked with a frequency mismatch of 20 MHz.

In the absence of the optical feedback from the external resonator, the lasers generate Q-switched pulses in the TEM_{00} mode and a single longitudinal mode with a pulse duration of 5.5 ns. The combined pulse energy from the two elements at the output is 20 μJ. The time series of the output exhibit two sets of pulse trains. The timing jitter of the pulses relative to the front edge of the pump pulse is on the order of 1 μs. Fig. 2a shows the beam profile at the output mirror of the free-running lasers which is the incoherent addition of the far-field profiles of the individual lasers. Due to a small deviation from perfect parallelism between the two end surfaces of the laser crystal, there exists a frequency mismatch between the lasers, which manifests itself as two sets of concentric fringes in the interferogram as viewed through the etalon. The frequency mismatch between the two lasers can be continuously controlled from zero to 1 GHz by rotating the crystal around the axis by 90°. The resolution of the etalon is 160 MHz. Smaller frequency mismatches that cannot be resolvable by the etalon can be inferred from the angular position of the laser crystal measured from the position of zero frequency mismatch. From the maximum fre-

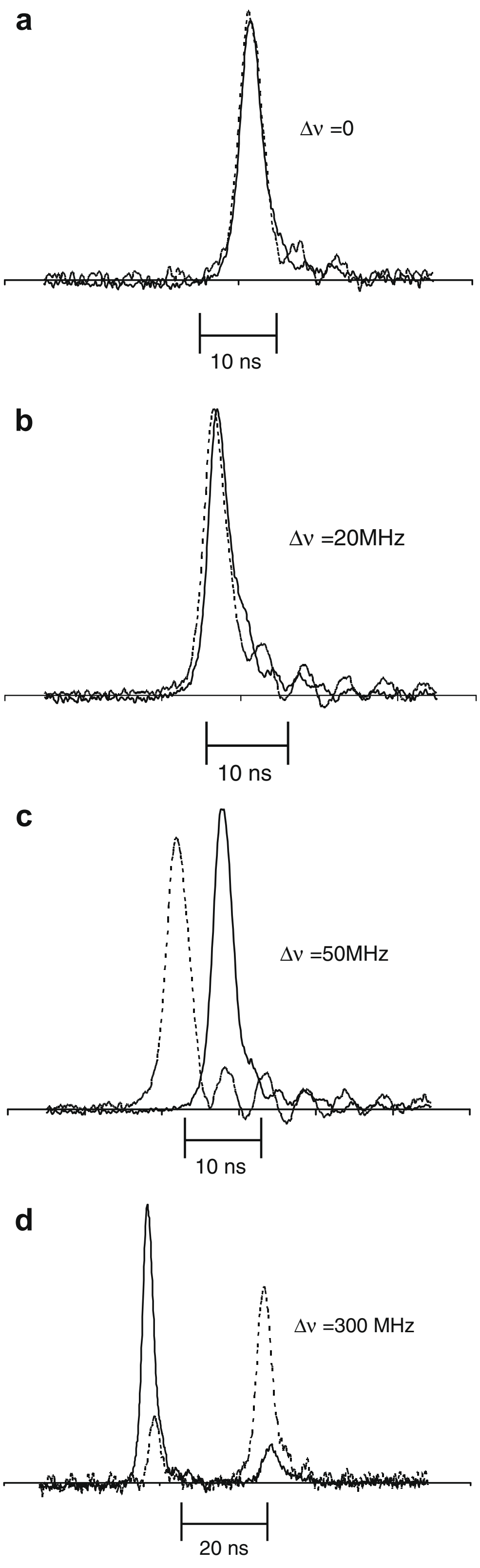

Fig. 3. Oscilloscope traces of phase-locked Q-switched pulses with (a) at zero frequency mismatch and (b) at frequency mismatches of 20 MHz, (c) 50 MHz, and (d) 300 MHz.

quency mismatch and the center-to-center spacing of 500 μm, we estimate the maximum wedge angle between the end surfaces to be $7''$.

3. Results and discussion

When the external cavity is properly aligned and the frequency mismatch set to zero, the two lasers generate pulses with equal intensity and perfect coincidence. The beam profile of at the output mirror S2 exhibits the fringe pattern of either the in-phase or out-of-phase modes and irregularly switches between the two modes from shot to shot. The fringe spacing is 160 μm, which is consistent with that calculated from the separation of the two lasers and the focal length of the external resonator. To stabilize the phase relation, a single 65 μm-diameter wire is placed in front of the output mirror as the spatial filter to create a higher loss for the out-of-phase mode. With the filter in place, the contrast ratio of the fringe pattern increases dramatically and the pattern remains stationary. Fig. 2b shows the beam profile of the in-phase mode. The total output pulse energy of the phase-locked laser is 26 μJ, which is 30% higher than the total pulse energy of the two lasers in the free-running mode. Fig. 3a shows the oscilloscope traces of the pulses from the individual elements when the frequency mismatch is nearly zero. Under this condition, the two pulses coincide precisely in time.

As the frequency mismatch between the two elements increases, the fringe visibility at the output mirror gradually deteriorates. Fig. 4 shows the fringe visibility as a function of frequency mismatch between the two elements. The combined output also successively exhibits pulse broadening, double pulsing, and complete separation of pulses as the frequency mismatch increases. As an example, the far-field pattern of reduced contrast taken at $\Delta\nu = 20$ MHz is shown in Fig. 2c. The corresponding oscilloscope traces of the pulses from individual elements are shown in Fig. 3b. The reduced fringe contrast and broadened pulses are due to the emergence of a relative time delay between the pulses from the individual elements. The relative time delay increases with increasing frequency mismatch and the two pulses become completely separated in time at $\Delta\nu = 50$ MHz, as shown in Fig. 3c. With increasing frequency mismatch and decreasing optical feedback, by tilting and misaligning the external cavity mirror, a relative delay as large as 50 ns has been observed. An example of the pulse pairs separated by 20 ns at $\Delta\nu = 300$ MHz is shown in Fig. 3d. We note that, while the pulses generated by the two elements in the free-running mode exhibit a large timing jitter on the order of a microsecond, the relative timing jitter between the pulse pair is zero. The fringe visibility of 0.2 at frequency mismatch >50 MHz, shown in Fig. 4, when the laser pulses from the two lasing elements are totally separated is caused by multiple passes of the single pulses in the external resonator.

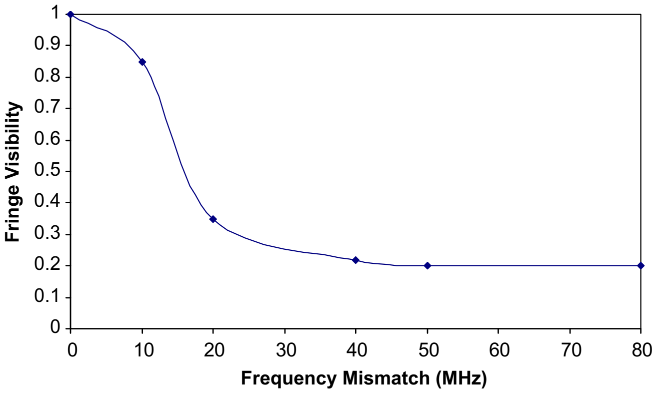

Fig. 4. Fringe visibility of the laser output as a function of frequency mismatch between the two lasing elements.

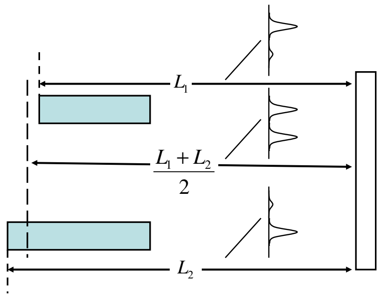

Fig. 5. Diagrams illustrating two lasers of unequal lengths coupled to a common external resonator and the intensity profiles of various spatial modes.

The observed dynamics of the phase-locked mode and transition between the locked and unlocked states can be explained based on the competition among the various eigen modes in the laser array [2]. Although the passively Q-switched laser pulses are only 5 ns in duration, the process of laser intensity amplification from the initial spontaneous emission to the intensity level which is strong enough to bleach the saturable absorber is long. Thus the mode selection during the building-up period follows the same mechanism as in the continuous-wave lasers. We base our discussion on the model of two lasers of unequal lengths coupled to an external resonator as illustrated in Fig. 5. When the two elements have unequal lengths, the operating frequencies cannot satisfy the resonance conditions in both elements simultaneously and the modal profiles of the transverse modes are determined by the proximity of the frequencies to the various longitudinal modes. The symmetric modes, presumably resonant with the cavity whose length is the average of the two, generate two pulses of equal amplitudes in the individual elements simultaneously. However, the symmetric modes, being off resonance in both elements, are not favored unless the two elements are nearly equal in lengths. In the presence of a large frequency mismatch, the dominating modes are expected to operate at the frequencies in the vicinity of the resonances of the individual elements. The spatial profiles of these modes are asymmetric with the stronger intensity residing in the element which is closer to resonance. The saturation of the saturable absorber further enhances the stronger element due to the reduced absorption loss caused by the stronger intensity. This process leads to the Q-switching pulse appearing in one of the elements first. The leading pulse then initiates the pulse in the other element, at a slightly different center frequency, by the coupling through the external resonator. The coupling is an injection seeding process whose strength depends on the frequency mismatch relative to the spectral bandwidth of the laser pulse. When the resonance frequency of one of the elements falls within the spectral bandwidth of the laser, which is estimated to be 60 MHz, the coupling is strong and the relative time delay of the pulses can be smaller than the pulse duration. These partially overlapping pulses create a stable interference fringe but with reduced contrast ratio. When the frequency mismatch is larger than the spectral bandwidth, the coupling is weak and the trailing pulse can be totally separated from the leading pulse. Because of this interaction, the relative timing jitter is nearly zero even though the pulses are widely separated in time.

Our study shows that the frequency mismatch in the Q-switched laser array causes a relative time delay between the pulses from the individual elements. The trailing pulses is initiated by the leading pulse and, for a given frequency mismatch, maintains a fixed time delay without a timing jitter. This results in a situation where the pulses from the individual element are temporally coherent but spatially incoherent. To create phase locking with a high degree of spatial coherence, which is needed for most applications, the frequency mismatch must be reduced to much less than spectral bandwidth of the laser pulses. To achieve a frequency mismatch of less than 20 MHz between two elements separated by 500 μm, the two planar surfaces of the laser crystal must be parallel to within 0.14″, which is not achievable using standard polishing techniques. This stringent requirement of parallelism rules out the possibility of forming a two-dimensional phase-locked solid-state laser array in a single crystal, but still permits one-dimensional laser array to be formed along the direction of minimum wedge angle.

4. Conclusion

We have studied the effects of frequency mismatch on phase locking of two passively Q-switched lasers. Stable phase locking with a high degree of spatial coherence in the combined beam can be obtained when the frequency mismatch is less than the spectral linewidth of the laser pulses. As the frequency mismatch increases, the transition from the phase locked to the unlocked states is characterized by a gradual loss of coincidence of the pulses from the individual elements and a reduction in the fringe contrast. The observed phenomena can be explained based on the dynamics of the asymmetric spatial modes in the laser array.

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