Letter

Misalignment sensitivity in an intra-cavity coherently combined crossed-Porro resonator configuration

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Abstract
We investigate the misalignment sensitivity in a crossed-Porro resonator configuration when coherently combining two pulsed multimode Nd:YAG laser channels. To the best of our knowledge, this is the first reported study of this configuration. The configuration is based on a passive intra-cavity interferometric combiner that promotes self-phase locking and coherent combining. Detailed misalignment sensitivity measurements are presented, examining both translation and angular deviations of the end prisms and combiner, and are compared to the results for standard flat end-mirror configurations. The results show that the most sensitive parameter in the crossed-Porro resonator configuration is the angular tuning of the intra-cavity interferometric combiner, which is $\pm 54 \, \mu\text{rad}$. In comparison, with the flat end mirror configuration, the most sensitive parameter in the resonator is the angular tuning of the output coupler, which is $\pm 11 \, \mu\text{rad}$. Thus, with the crossed-Porro configuration, we obtain significantly reduced sensitivity. This ability to reduce the misalignment sensitivity in coherently combined solid-state configurations may be beneficial in paving their way into practical use in a variety of demanding applications.

Keywords: coherent combining, Porro-prism resonators, laser resonators, resonator misalignment sensitivity

(Some figures may appear in colour only in the online journal)
per pulse [7]. Until now, intra-cavity coherent combining has only been demonstrated with flat or concave rear mirrors and a flat or concave output coupler. However, such resonators are known to be highly sensitive to mirror misalignments; a tilt of tens of μrads results in a 10% degradation in terms of output power in a typical resonator [12].

In field- and space-deployed lasers, i.e. range-finders, LIDARS etc, where the environmental conditions vary significantly, plano–plano configurations are seldom used. The common solution to reduce misalignment sensitivity in these types of lasers is to use crossed-Porro prisms as the resonator end mirrors, together with a waveplate and a polarized beam splitter as the output coupler [12]. The misalignment sensitivity of such crossed-Porro prism single-channel resonators has been thoroughly investigated [13]. The crossed-Porro prism resonator was found to be less sensitive to tilt misalignment by a factor of 30 in comparison with a flat mirror resonator. The use of Porro prisms in conventional laser applications (i.e. not field or space deployed) also has the benefit of alleviating manufacturing tolerances and facilitating long term alignment-free operation.

Passive coherent beam combining has so far not been commercially exploited in laser systems, and there is an open question as to the precision tolerances that are required when a crossed-Porro resonator configuration is used for intra-cavity coherent combining. This configuration typically involves complex multi-channel oscillator designs, with interferometric beam combining within the cavity. As opposed to single channel oscillators where there is a need to compensate only for angle tilts of the lasing axis, in multi-channel oscillators there is also a need to maintain spatial overlap of the beams on the beam combining elements. Hence, it is unclear to what extent the crossed-Porro prisms decrease the misalignment sensitivity with regard to equivalent plano–plano configurations.

In this paper we study the use of Porro prisms for coherently combining two intra-cavity multimode solid-state laser channels. To the best of our knowledge, this is the first time where the use of Porro prisms in a passive multichannel coherent combining configuration is investigated, and where the misalignment tolerances are measured and compared to those achieved with plane mirrors (part of this work was recently presented in a conference [14]). We show that with the crossed-Porro resonator configuration, we obtain significantly reduced sensitivity (five-fold) to tilt misalignments, while maintaining the combining efficiency and the beam quality. This result is similar to the known effect of Porro prisms in standard single channel configurations, yet because of the configuration complexity it is in general non-intuitive, and, up until the current study, has not been quantitatively measured or analyzed. We believe this is especially important for demanding applications where harsh environmental conditions are present (temperature, vibration, etc), even if the multichannel laser configuration only has a small number of combined channels. We note that the issue of the scalability of passive coherent combining to a large number of channels is not considered within the scope of this paper.

In the following we focus on four distinct multimode Nd:YAG laser configurations: (a) a plano–plano single channel resonator; (b) a crossed-Porro single channel resonator; (c) two coherently combined channels in a plano–plano resonator; and (d) two coherently combined channels in a crossed-Porro resonator. The first two configurations are characterized in order to establish a baseline for comparison between the latter configurations.

2. Experimental setup, results and discussion

The schematics of the single channel resonator configurations are shown in figure 1. The plano–plano resonator, figure 1(a), is 90 cm long. The output coupler reflectivity is 80% and the rear mirror is highly reflective (HR) (both at 1064 nm). The active medium is an Nd:YAG rod, 8 cm long and 4.5 mm in diameter. The Nd doping concentration in the laser rod is 0.65 at.%. The rod is side pumped with 808 nm diodes, and passively cooled. The temperature of the pump diodes was stabilized using a thermoelectric cooler. The experiments were conducted far above threshold. The intra-cavity aperture diameter was 3 mm. An intra-cavity Galilean telescope of ×2 magnification was inserted to ensure low energy density on the right side of the cavity, and a polarizing beam splitter (PBS) ensured linear polarization. As shown in figure 1(b), the crossed-Porro resonator is similar to the plano–plano resonator with the following differences: the rear mirror was replaced by a Porro prism, and the output coupler was replaced by a Porro prism, placed perpendicular to the first Porro prism. This configuration compensates for some of the active medium’s birefringence. The Porro prisms are HR and produce a 74° phase shift between s- and p-polarization for a BK7 glass prism [15]. In addition, a quarter wave plate, whose angle determines the output coupling reflectivity, was placed before the PBS.

In the plano–plano aligned cavity (see figure 1(a)) the measured output pulse energy was 30 mJ and the beam quality parameter was $M^2 = 3$. Each laser channel operated in free-running mode (non Q-switched), 10 Hz repetition rate, with an average power of about 0.3 W. The beam quality parameter was measured with a Spiricon LBA beam analyzer using the $4\sigma$ method. A COHU 4812 CCD camera was used in order to measure the near-field (NF) intensity distribution, with the addition of a lens with a focal length of 1500 mm in order to measure the far-field (FF) intensity distribution. Figure 2 shows the normalized measured output pulse energy for the
single channel plano–plano configuration as a function of the misalignment tilt angles (rear mirror, output coupler). Angles phi and theta correspond to the vertical and horizontal axes, respectively (in the case of the prisms, the tilt axes correspond to the prism axes). All tilt angles were measured using a HeNe reflection at a distance of 8.6 m. The angle measurement uncertainty was 15 $\mu$rad. We have chosen to define the misalignment tolerance of a specific element as the tilt angle which results in a 10% decrease in output power. The power was measured for several misalignment values and the 10% decrease point was determined using an interpolation between the measured values. The misalignment sensitivity of a laser configuration can be considered to be the misalignment sensitivity of the most sensitive element. As is evident, the output coupler is more sensitive to misalignment than the rear mirror. We attribute this to the cavity asymmetry due to the angular magnification of the intra-cavity telescope. When we measured the angle misalignment sensitivity without the telescope, the sensitivities of the output coupler and the rear mirror were similar. The misalignment tolerance of the resonator is 14.5 $\mu$rad. With the crossed-Porro single channel resonator configuration (see figure 1(b)) the measured output pulse energy was 29.5 mJ and the beam quality parameter was $M^2 = 2.7$. Figure 3 shows the angle misalignment tolerances in a single channel crossed-Porro resonator. The most sensitive element was the right Porro prism (theta angle), with a misalignment tolerance of 230 $\mu$rad. As expected, this configuration is significantly less sensitive than the plano–plano configuration. Note that the theta angle of the left Porro prism and the phi angle of the right Porro prism were relatively insensitive, as expected.

Next, we built and characterized the two-channel coherently combined laser configurations, both with plano–plano mirrors and with crossed-Porro prisms. The detailed configurations are shown in figure 4. Both configurations are similar to the corresponding single channel configurations, with the addition of a second channel that consists of a rear reflecting element, a gain element, and a HR mirror with a 50% beam splitter for combining both channels. Note that the alignment of the multichannel resonators was not trivial at all, and required the use of laser reflections from the first channel to align the elements in the second channel. The measured NF and FF intensity distributions of the output beam from the single channel crossed-Porro configuration and from the two-channel coherently combined crossed-Porro configuration are shown in figure 5. It is evident that the beam distributions are symmetrical and are typical of multimode operation. The beam quality is slightly improved in the two-channel configuration (in agreement with previous reports [7]), with $M^2 = 2.2$, instead of $M^2 = 2.7$ for the single channel crossed-Porro configuration. The combined output pulse energy was 57.5 mJ, corresponding to a combining efficiency of 97%.
in a single channel resonator configuration. The misalignment measurements for the two-channel plano–plano configuration are shown in figure 6. The most sensitive tilt is 11 µrad. When coherently combining two channels in the plano–plano configuration, the end mirrors are more sensitive to tilt misalignments in comparison with the interferometric combiners. The results for the two-channel crossed-Porro configuration are shown in figure 7. The most sensitive tilt is 54 µrad. When coherently combining two channels in a crossed-Porro configuration, the sensitive axis of the prisms is less sensitive to tilt misalignments in comparison with the interferometric combiners. This is expected because of the tilt tolerance of the Porro prisms, but is in contrast to plano–plano resonators where typically the end-mirrors are the most sensitive to tilt misalignments. In general, thermal lensing in the gain elements of a coherently combined system will have an effect on the combining efficiency, if not properly compensated [8]. When working at higher repetition rates the thermal lensing will be larger. In figure 8 it is shown that in both configurations (plano–plano and crossed-Porro prisms) higher repetition rates lead to a similar decrease in the combining efficiency. The maximum combining efficiency occurs at 10 Hz since the alignment of the cavity was conducted at that repetition rate.

In the single channel crossed-Porro resonator configuration, a translation of 0.1 mm and 0.7 mm of the left Porro prism and the right Porro prism, respectively, results in a 10% decrease in output energy. Without the intra-cavity telescope, the sensitivity of the right Porro prism to translation reduced to 0.25 mm. As with tilt sensitivity, we attribute this difference in translation sensitivity to the cavity asymmetry due to the angular magnification of the intra-cavity telescope. We observed no significant changes in translation sensitivity in the two-channel coherently combined crossed-Porro resonator configuration. We measured the beam quality sensitivity to tilt and translation misalignments in each of the four configurations (end mirrors, prisms, and combining elements). Although the tilt and translation misalignments (within the 10% decrease in output energy) resulted in a slight asymmetry in the output beam profile, we observed an increase of only a few percent in the $M^2$ parameter. This means that within the regime of a 10% decrease in output energy, the beam quality is
crossed-Porro NF and FF intensity distributions, respectively (Porro phi misalignment); (c) and (d) two-channel crossed-Porro NF and FF intensity distributions, respectively (Porro theta misalignment).

In summary, we have investigated misalignment sensitivity when coherently combining two Nd:YAG channels in a crossed-Porro resonator configuration. When we coherently combined two channels, the most sensitive tilt misalignment angle was ±11 μrad for the plano–plano configuration and for the crossed Porro configuration it was ±54 μrad. This reflects an almost five-fold decrease in sensitivity with regard to the plano–plano configuration. In terms of the specific elements in the resonator, the results show that the combining elements are less tilt sensitive than the end mirrors in the plano–plano configuration, and the reverse is the case for the crossed-Porro configuration.

Figure 9. Measured misaligned output beam intensity distributions. (a) and (b) two-channel crossed-Porro NF and FF distributions, respectively (Porro phi misalignment); (c) and (d) two-channel crossed-Porro NF and FF intensity distributions, respectively (Porro theta misalignment).

Table 1. Most sensitive tilt misalignment in each studied case.

| Number of channels | Configuration  | Most sensitive tilt misalignment (μrad) |
|--------------------|----------------|----------------------------------------|
| 1                  | Plano–plano    | ±15                                    |
| 1                  | Crossed-Porro  | ±230                                   |
| 2                  | Plano–plano    | ±11                                    |
| 2                  | Crossed-Porro  | ±54                                    |

not significantly affected by the misalignment. In figure 9 we show an example of the measured output intensity distribution for a case with tilt misalignment (10% energy decrease).

In table 1 we list the magnitude of the most sensitive tilt misalignment in each studied case (single and two-channel, plano–plano and crossed-Porro, 10% decrease in output power). Finally, we operated our system in a Q-switched mode using an RTP crystal placed in the common channel near the right Porro prism. The high voltage to the RTP pockels cell was tuned to quarter wave retardation. All measurements were done without realigning the RTP (when tilting the end mirrors or combining elements). The measured pulse duration was 20 ns, with 57.5 mJ pulse energy, corresponding to a combining efficiency of 97%. The tilt angle misalignment sensitivity in the Q-switched operation, as measured by a few representative misalignment tilts, was similar to the misalignment sensitivity in free-running mode. This indicates that our free-running misalignment measurements also provide a good estimation for Q-switched operation.

3. Conclusions

In summary, we have investigated misalignment sensitivity when coherently combining two Nd:YAG channels in a crossed-Porro resonator configuration. When we coherently combined two channels, the most sensitive tilt misalignment angle was ±11 μrad for the plano–plano configuration and for the crossed Porro configuration it was ±54 μrad. This reflects an almost five-fold decrease in sensitivity with regard to the plano–plano configuration. In terms of the specific elements in the resonator, the results show that the combining elements are less tilt sensitive than the end mirrors in the plano–plano configuration, and the reverse is the case for the crossed-Porro configuration.

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