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# Efficient uni and bi-directional oscillations in photorefractive ring resonators

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## ABSTRACT

We have demonstrated efficient amplification of 830 nm and 1.06 μm light in a ring resonator using Rh:$BaTiO_3$. The power oscillating inside the ring exceeded the pump power by up to a factor of 2.3 at 1.06 μm. We have also showed that such an efficiently working photorefractive cavity is also sensitive to nanometer changes in its cavity length. We have also observed simultaneous, bi-directional and counterpropagating oscillations in a resonator pumped by a single 647 nm pump beam. The intensity of one oscillation beam was up to two orders of magnitude higher than the intensity of the other oscillation beam.

**Keywords:** Photorefractive nonlinear optics, Resonators, Two-wave mixing, Dynamic sensing

## 1. INTRODUCTION

The first successful demonstrations of unidirectional ring resonators were carried out by White *et al.*[1], Kwong *et al.*[2] and Ewbank *et al*[3]. Several unique aspects of photorefractive resonators have been extensively investigated over the past few years. For example, their dynamics[4], stability[5] and coherence[6] effects have been theoretically analysed and described in some detail[7].

A unidirectional ring resonator has a geometry tolerant to the position of a photorefractive crystal in the cavity and the incidence angle of the pump beam. The gratings that develop inside the crystal, as a result of an interaction of the pump beam and scattered light, are self-adaptive and self-building up. The resonating beam, that originates from scattered light, gains energy from successive multi-pass, two-beam coupling amplification process on each round trip through the photorefractive material. It accumulates energy until saturation sets in, but also loses energy through the resonator via absorption, Fresnel reflections from the crystal and imperfect mirrors. Therefore, the condition for the build-up of the resonating requires the coupling efficiency to exceed the combined absorption and resonator losses. If losses and absorption are small, a ring resonator has the capability of providing large amplification of weak signals and being very sensitive to minute changes in its length.

The main indication of the performance of a photorefractive ring resonator is the conversion efficiency - defined as the ratio of the resonating beam power to the power of the external pump beam. This depends on the out-coupling mirror reflectivity, the two-beam coupling coefficient, the length of the interaction region inside the photorefractive material, and on the effective absorption coefficient that includes combined losses from the crystal, absorption, mirror and Fresnel reflection losses[8]. The conversion efficiency can be larger than 100% if the coupling coefficient significantly exceeds all other cavity losses.

In this paper we show that, in agreement with parameters established earlier[9], high convèrsion efficiency in a ring resonator is possible when using a near-to-optimum wavelength and low absorption. We also present the dynamics of the amplified resonating beam and the issues related to its stability, response time and grating formation depending on the incident wavelength and crystal absorption.

## 2. UNIDIRECTIONAL RESONATOR PUMPED BY NEAR-INFRARED LIGHT

### 2.1 Experimental details

The experimental set-up consisted of three mirrors and a photorefractive crystal, selected for its good infrared sensitivity pumped by a cw, single longitudinal mode infrared laser. In the first set-up we used a diode-pumped 300 mW Nd:YAG laser emitting light at 1.06 µm and in the second resonator a 100 mW, 830 nm diode laser. Figure 1 presents a schematic diagram of the experimental configuration.

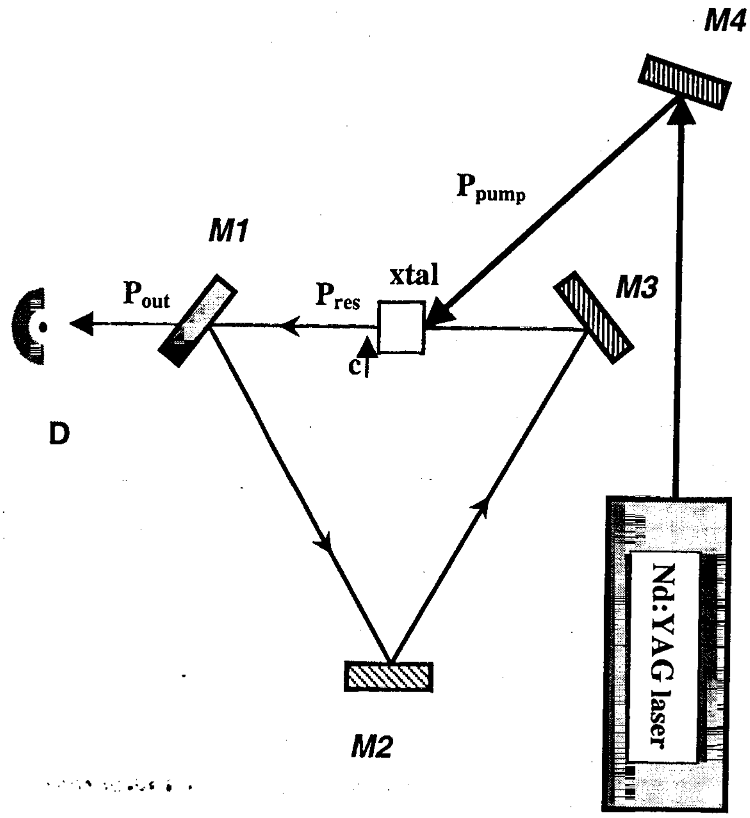


**Figure 1.** Experimental set-up for observing oscillations in a ring resonator. M2-M4 – 99.9% reflecting mirrors, M1 – partially reflecting mirror, D- power meter.

When the two-beam coupling gain exceeds all the cavity losses, the resonating beam builds up from the progressive amplification of fanned light. The circulating power is measured by monitoring the power of the light transmitted by the output coupler of the cavity (R = 95%). The power of light resonating inside the cavity is calculated from the measurement of out-coupled power and the reflectivity of the coupler. In order to minimise the losses of the resonator, the remaining mirrors are 99.9% reflective. With either the miniature Nd:YAG laser or a diode laser, the experimental set-up could be made quite compact. The length of the 830 nm resonator was 62 cm while the 1.06 µm resonator was 52 cm long. For the tests of the cavity sensitivity to the changes of path length, one of the high reflecting (R=99.9%) mirrors was mounted on a piezoelectric actuator.

In our earlier theoretical studies[9] we established that low absorption coefficient (0.1 - 0.2 $cm^{-1}$) and low cavity losses are the most crucial parameters for an effective operation of a resonator. This criterion determined the choice of photorefractive crystals used for the experiments. In the 830 nm resonator we used JackB sample (3200 ppm $Rh:BaTiO_3$ reduced) with coupling coefficient of 10.6 $cm^{-1}$ and an absorption coefficient 0.5 $cm^{-1}$ at this wavelength. In the 1.06 μm resonator we used Dan (1000 ppm $Rh:BaTiO_3$) crystal that has a coupling coefficient of 10.1 $cm^{-1}$ and absorption coefficient of 0.05 $cm^{-1}$ at 1.06 μm and JackA crystal (1400 ppm $Rh:BaTiO_3$) that has a coupling coefficient of 10.4 $cm^{-1}$ and 0.07 $cm^{-1}$ at this wavelength.

### 2.1 Results on amplification of resonating light

In our experimental work we observed that infrared ring resonators can work efficiently with several different samples of $Rh:BaTiO_3$ at 1.06 μm wavelength. As expected, the highest conversion efficiency was achieved for the samples with the lowest absorption. Table 1 gives the details of optimum amplification achieved in two samples investigated. For example, in the Dan sample, we measured a build-up of power inside the resonator exceeding the pump beam by up to a factor of $\xi_{exp}$=2.2. The maximum power outcoupled from the cavity was 29.3 mW which indicates that the power of the beam resonating inside the cavity was 586 mW (for an incident pump of 250 mW). The experimentally determined value agrees quite well with the theoretical predictions[8], shown in Table 1 as $\xi_{th}$. Although absorption coefficients of the crystals were small in both samples, $\alpha_{eff}$ - the effective absorption coefficient, has to be considered in all estimates of the resonator efficiency. $\alpha_{eff}$ includes combined losses from the crystal, absorption, mirror and Fresnel reflection losses.

**Table 1.** Performance of ring resonators with $Rh:BaTiO_3$ crystals pumped by 830nm and 1.06 μm light.

| Crystal | $\lambda_{pump}$ | $\Gamma$ [$cm^{-1}$] | $\alpha_{eff}$ [$cm^{-1}$] | $P_{res}$ [mW] | $\xi_{exp}$ | $\xi_{th}$ |
|---|---|---|---|---|---|---|
| Dan | 1.06 μm | 10.1 | 0.59 | 560 | 2.2 | 2.4 |
| JackA | 1.06 μm | 10.4 | 0.69 | 586 | 2.3 | 2.3 |
| Jack B | 830 nm | 10.6 | 1.12 | 87 | 0.87 | 1.5 |

As shown in Table 1, we also demonstrated a ring resonator working with an 830 nm pump. Its efficiency was, as expected, below 100% ($\xi$ < 1) because of higher crystal absorption at this wavelength. Nevertheless, up to 87% of the incident pump power was converted into an oscillation beam that built-up approximately an order of magnitude faster than in the case of a 1.06 μm pump beam.

### 2.3. Dynamics, stability and the sensitivity of resonating beam to cavity changes

We were also interested in the dynamics and stability of the resonating beam. As with any optical cavity, its correct alignment is critical for achieving oscillations. Although photorefractive ring resonators can adapt their operation to different cavity lengths, they are as sensitive to misalignment and tilts as any other cavity. Minute cavity distortions can prevent the build up of oscillations or if the degree of misalignment is small, cause additional, high-order modes to appear[10]. Typically, when the resonating beam is oscillating in several modes, its intensity is lower than in the one transverse mode case and is also more susceptible to instabilities. Figure 2a and figure 2b show a typical example of the difference between the correctly aligned and misaligned cavity.

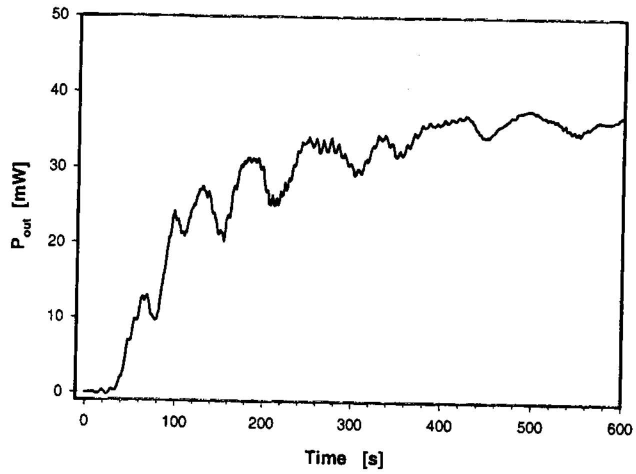


**Figure 2a** Stable build-up of a beam resonating in one transverse mode

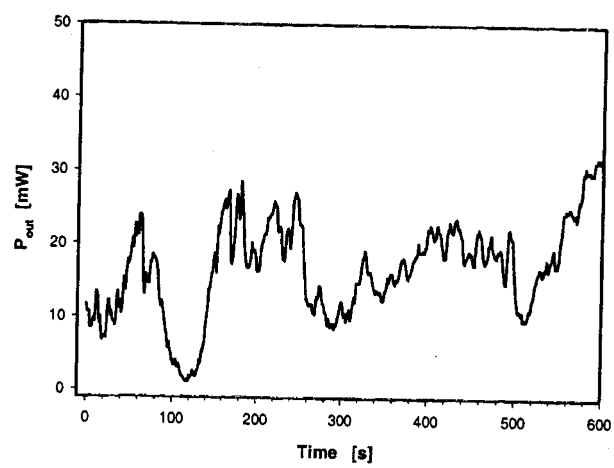


**Figure 2b** Unstable oscillation of a beam resonating in more than one transverse mode

The quality and the correct cut of the samples is another important parameter, as even a minute nonuniformity of the sample's cut can distort the path of the resonating beam and prevent efficient mixing with the pump beam. However, once a cavity is aligned, the crystal can be rotated and the pump beam incidence changed to optimise and achieve the best interaction geometry.

Finally, we determined the sensitivity of the resonating beam intensity to cavity path length changes. We attached a piezo-mirror driver to mirror M2 and varied its position in sub-nanometer steps. We established that such sub-nanometer changes could be detected via monitoring changes in the intensity of the resonating beam. Figure 3 shows the variation in the oscillation beam intensity with time as the cavity piezo mirror is moved by up to 1.5 nm. Such high sensitivity to nanometer changes in cavity length is ideally suited for sensing applications where, for example, minute concentrations of trace species could be measured.

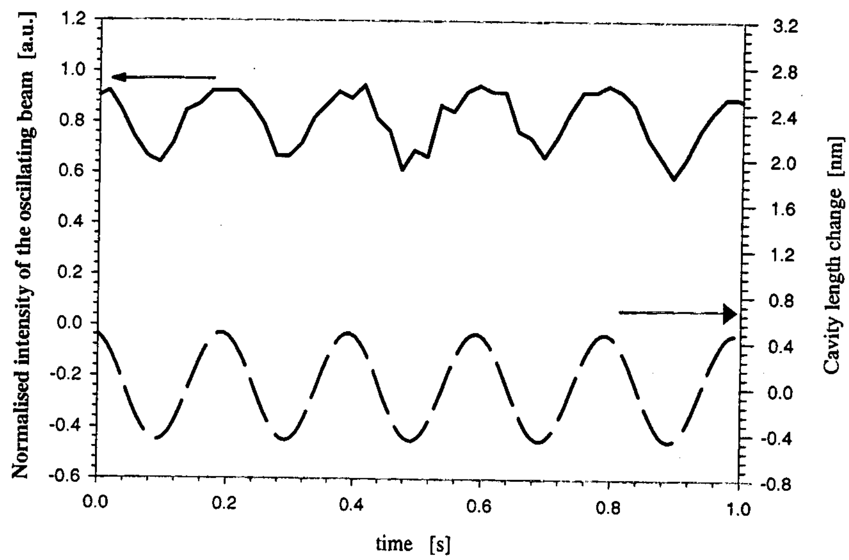


**Figure 3.** Intensity of the resonating beam as a function of the displacement of a piezo mirror. The piezo is periodically moved by up to ± 1.5 nm and the resonating intensity follows the cavity changes. Solid line: resonating power signal, dashed line: variation in cavity length.

## 3. BIDIRECTIONAL RESONATOR PUMPED BY VISIBLE LIGHT

In the ring resonator, based on two-beam coupling effect, the pump beam incident on the crystal fans towards the +c face and some of the fanned light is directed around the loop to re-enter the crystal, via the three mirror set-up. The light in this ring is unidirectional because the two-beam coupling gain is itself directional, as determined by the crystal's symmetry, alignment and the charge transport properties. Any backward travelling light will experience loss and therefore will not get amplified as observed in previous experiments on photorefractive resonators[1]. As explained earlier, if the two-beam coupling gain is above threshold, the unidirectional resonating beam will build up from the progressive amplification of this fanned light. However, we observed that bidirectional oscillation can be achieved in a ring resonator pumped by a single pump beam. Such bidirectional oscillation can be selected by using an appropriate incident pump angle and crystal orientation.

### 3.1 Experimental set-up

The experimental set-up was similar to those presented in figure 1. As a pump beam we used visible light at 647 nm from a $Kr^+$ laser to pump a 10 × 10 × 10 mm $Ce:BaTiO_3$. This crystal had a relatively high coupling coefficient ( $\Gamma = 10cm^{-1}$), combined with low absorption ($\alpha$=0.2 $cm^{-1}$) in the visible and was therefore well suited for a ring resonator application with a 647 nm pump beam. In the initial geometry, the pump beam was incident on the *a*-face of the crystal. The circulating power was monitored by out-coupling light via a beam splitter placed inside the cavity. The cavity itself was 2 meters ± 2 cm long. The cavity mirrors were 99% reflective.

### 3.2 Bidirectional oscillation results

We discovered that a single ring cavity could simultaneously support two counter-propagating oscillation beams despite the photorefractive crystal's symmetry[11]. This is the first observation, to our knowledge, of bidirectional oscillation in a single ring configuration. Figure 4 presents the experimental data on temporal power development of both beams.

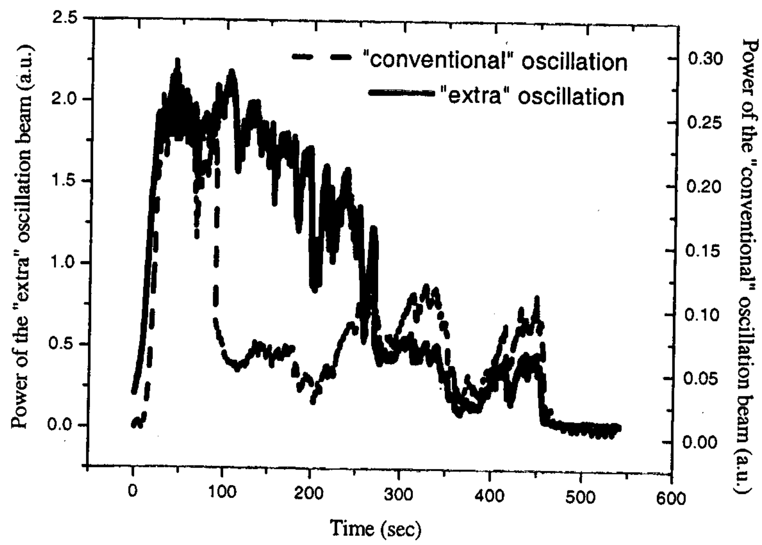


**Figure 4** Bidirectional oscillation with a single pump beam incident on *a*-face of $Ce:BaTiO_3$ crystal. Thick solid line: extra oscillation beam; dashed line: conventional oscillation.

For clarity, the normal oscillation that grows from two-beam coupling is labelled as the "conventional" beam, and the unexpected counterpropagating beam as the "extra" beam.

Although both oscillation beams eventually decayed in time, the extra oscillation beam power took 400 seconds longer to decay then the conventional beam. The decay time depended on the geometry of interaction and with different incidence pump angles, it could be shown that both beams did not decay even after 600 seconds. We think that the limited coherence length of the multi-longitudinal 647 nm pump beam is responsible for this decay of oscillations.

The build-up of the extra oscillation beam as well as its high power, over sixty times larger than the conventional beam, are the two unexpected features of this ring resonator operation. In fact, we measured that the extra beam power oscillating inside the cavity could exceed the pump beam by a factor of 1.25, demonstrating the efficient ring resonator with bidirectional operation. However, the conventional oscillation beam reached power levels only as high as 0.02 of the pump beam power.

In order to investigate the origin of the extra oscillation beam, we checked other positions of the pump beam incidence and the crystal's rotation. With the pump beam incident on the *+c* face of the crystal, as with the *a*-face incidence, bidirectional oscillation was again observed for a broad range of incidence angles. Analysing and inspecting the beam paths both inside the crystal and in the ring resonator, we were able to identify the origin of the extra beam as arising from additional cavities formed by highly polished faces of the crystal. For example, we observed an internal loop inside the crystal (internal ring resonator). The extra oscillation beam disappeared if this internal loop was made to disappear via selecting the appropriate pump incidence angle and rotating the crystal. The internal loop seems to form in such a direction, that the extra oscillation beam can gain energy from it. It is likely that the large and well polished samples of high gain photorefractive materials, such as the 10×10×10 mm Ce:$BaTiO_3$, are capable of simultaneously sustaining multiple gratings, both based on two-beam coupling and self-pumped phase conjugation. Although this explanation is just qualitative, it nevertheless provides general background and description of effects we observed. The full analysis would need to involve six-wave mixing theoretical modelling as well as the modelling of the evolution of coherence, a problem which cannot be solved analytically for our case.

The results of experiments described in this paper and performed during this course of our study show that that the nature of interactions occurring in the photorefractive ring resonator is more complex than expected and predicted by the existing theory and need to be investigated in more detail to gain better understanding.

## 4. CONCLUSIONS

We have presented photorefractive ring resonators working efficiently at both visible and near-infrared wavelengths. At 1.06 μm, due to low absorption and sufficiently high coupling coefficients, significant amplification of a diffraction-limited oscillation beam could be achieved, exceeding the input pump beam power by over a factor of 2.3. We also studied the dynamics of the oscillations and, as expected, observed significant instabilities when the beam was resonating in several transverse modes. The highest efficiency and the best stability was observed for a single transverse mode oscillation.

We also observed that resonators, pumped by 830 nm and 647 nm, although less efficient because of higher absorption of photorefractive crystals, responded much faster. With a 647 nm pump beam we were able to induce bi-directional oscillations in a resonator. The two oscillation beams simultaneously propagated in opposite directions and the difference in their power reached up to two orders of magnitude.

The results obtained in the near-infrared regime were consistent with the theoretical modelling. However, the bi-directional oscillations and their dynamics were unexpected and not predicted by the existing theory. We studied this effect and were able to identify the phenomena responsible for it, namely additional internal resonators that formed inside photorefractive crystals.

## ACKNOWLEDGEMENTS

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