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COHERENT COMBINING OF OPTICAL PARAMETRIC OSCILLATORS: CHALLENGES AND EXPERIMENTAL DEMONSTRATIONS

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ABSTRACT:

Coherent combining (CBC) techniques are very efficient to power scale lasers to the multikilowatt level. However, high power fiber lasers are only available within a finite set of wavelengths, mainly amongst 1 μm , 1.5 μm and 2 μm . Hopefully, nonlinear crystals offer the capability to convert these laser lines to access higher wavelengths in the midinfrared bands, for instance between 3 and 5 μm .

In this paper, we present the challenges of applying coherent combining by active phase control to much more powerful frequency converters: optical parametric oscillators (OPO). An experimental demonstration of OPO CBC is also detailed.

1. INTRODUCTION

Coherent beam combining (CBC) techniques involving active phase control of the laser emitters have demonstrated their potential to power scale continuous-wave [1] and pulsed [2] fiber lasers through coherent addition of the power emitted by multiple separate amplifiers. Using all-fiber components, very compact configurations of coherently combined fiber amplifiers can be designed, with demonstrated overall emitted power exceeding the kilowatt level [1].

However, high power fiber lasers are only available within a finite set of wavelengths, mainly amongst 1 μm , 1.5 μm and 2 μm . Hopefully, nonlinear crystals offer the capability to convert these laser lines to access higher wavelengths in the midinfrared bands, for instance around 4 μm . But as with lasers, power scaling of frequency converters is limited, essentially by the damage threshold of the nonlinear medium. Coherent combining techniques would be extremely useful to power scale frequency converters beyond this damage threshold limit. Unfortunately, combination techniques are difficult to implement in this case, as active phase control requires fast phase modulators at the midinfrared wavelength emitted by the converter. Such components are not exactly

"off-the-shelf" and are not as practical nor as fast as the all-fiber modulators available at more standard wavelengths.

Fortunately, taking advantage of the phase-matching relations involved in any frequency converting process, one can indirectly control the converted wave phase through control of the pump wave phase. When this pump wave is delivered by fiber amplifiers, such a frequency-converter coherent combining configuration can be achieved using standard off-the-shelf all-fiber phase modulators. Our team successfully applied this approach to perform efficient coherent combination of second harmonic generators and difference frequency generators [3], [4], [5].

In this paper, we present the challenges of extending this indirect phase control technique to midinfrared OPO coherent combining.

An experimental demonstration of OPO CBC is also detailed. Results will be presented during the conference.

2. PRINCIPLE AND EXPERIMENTAL SETUP FOR CBC OF PARAMETRIC AMPLIFIERS

Coherent beam combining of non-degenerate three wave mixing nonlinear processes was first demonstrated on devices that didn't require a cavity to operate: difference frequency generators. But the theoretical bases are identical to those of OPO CBC, as both experiments combine parametric amplifiers.

To achieve CBC of DFGs or OPOs, phase control of one of the converted waves, the signal or the idler waves, has to be performed.

Indirect phase control benefits from the phase-matching condition.

The electric field corresponding to each nonlinearly coupled wave can be written as:

$$\tilde{E}_m(z, t) = A_m(z) e^{jk_m z} e^{-j\omega_m t} + c. c \quad (1)$$

with $m = s, i$ or p and A_m the complex amplitude of the ω_m pulsation wave.

If we assume that the pump wave is not depleted when passing through the crystal, which is true on the first millimeters of the nonlinear crystal where parametric amplification is still weak, the coupled-amplitude equations describing difference frequency generation are:

$$\begin{cases} \frac{dA_s(z)}{dz} = \frac{8\pi j \omega_s^2 d_{eff}}{k_s c^2} A_p A_i^*(z) e^{j\Delta k z} \\ \frac{dA_i(z)}{dz} = \frac{8\pi j \omega_i^2 d_{eff}}{k_i c^2} A_p A_s^*(z) e^{j\Delta k z} \end{cases} \quad (2)$$

where $\Delta k = k_p - k_s - k_i$.
Propagation equation of the idler wave is:

$$\frac{d^2 A_i(z)}{dz^2} = \kappa_s^* \kappa_i |A_p|^2 A_i(z) \quad (3)$$

with $\kappa_m = \frac{8\pi j \omega_m^2 d_{eff}}{k_m c^2}$. A similar equation can be written for the signal wave.

Maximum power conversion is achieved for perfect phase-matching condition, i.e. $\Delta k = 0$.

This system of equations can be solved, in the case of an unseeded idler wave $A_i(0) = 0$, into:

$$\begin{cases} A_s(z) = A_s(0) \cosh(\sqrt{\kappa_s \kappa_i |A_p|^2} z) \\ A_i(z) = \frac{\kappa_i A_p(0)}{\sqrt{\kappa_s \kappa_i |A_p|^2}} A_s^*(0) \sinh(\sqrt{\kappa_s \kappa_i |A_p|^2} z) \end{cases} \quad (4)$$

These solutions correspond to a signal field that keeps its initial phase-offset, and is simply amplified by the interaction, while the idler wave phase-offset depends on both the pump wave's and the signal wave's.

$$\varphi_i = \varphi_p - \varphi_s + \frac{\pi}{2} \quad (5-a)$$

Similarly, in the QPM case, high conversion efficiency can be achieved in a periodically poled crystal. The relation between the phases of the pump, signal and idler waves can be obtained propagating the waves in the crystal, domain by domain and step by step:

$$\varphi_i = \varphi_p - \varphi_s \quad (5-b)$$

Due to this phase relation, controlling the pump wave phase gives complete control of the idler wave phase. For instance, in the QPM case, a φ_{p0} phase shift induced on the pump wave will compensate for an idler wave phase variation of $\varphi_{p0} - \varphi_{s0}$, where φ_{s0} is the initial phase of the signal wave at the entrance of the nonlinear crystal. Consequently, phase control of DFG and OPO converters is achievable, using all-fiber electro-optic phase modulators to control the pump wave.

3. EXPERIMENTAL DEMONSTRATIONS OF DFG CBC

We demonstrated experimentally the feasibility of such indirect phase control combining two DFG modules pumped by 1.064- μm Yb: fiber lasers delivering up to 15 W power each.

To fix and maintain the signal wavelength and phase, it is necessary to seed the DFGs with a signal seed at 1553 nm from a laser diode

amplified by a commercial erbium-doped fiber amplifier split in two. Using this 1553-nm seeder, we are able to keep both DFG channels at a common and fixed signal wavelength.

The DFG nonlinear crystals are PPLN crystal from Covision and their length is $L = 20$ mm. With a 1064-nm pump wavelength and a seeded signal at 1553 nm, quasi-phase matching in the PPLN crystal is obtained with a poling period of 30.49 μm and at an operating temperature of 60 $^\circ\text{C}$ for both crystals, generating an idler wave at 3.4 μm . The pump beams are focused down to 100 μm waist in the PPLN crystals.

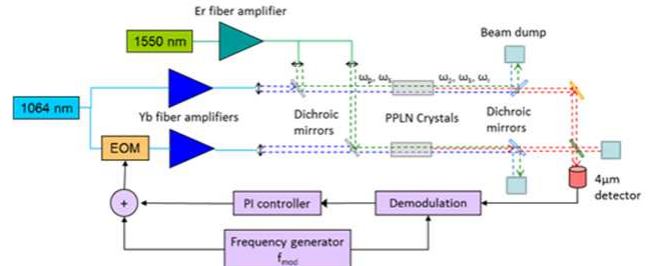


Figure 1. Schematics of the experimental setup for demonstrating CBC of two 3.4- μm difference frequency generators by phase-control of the 1.064- μm pump wave.

Coherent combining of these DFG modules is achieved using the idler waves interference signal to close the feedback loop (see figure 2).

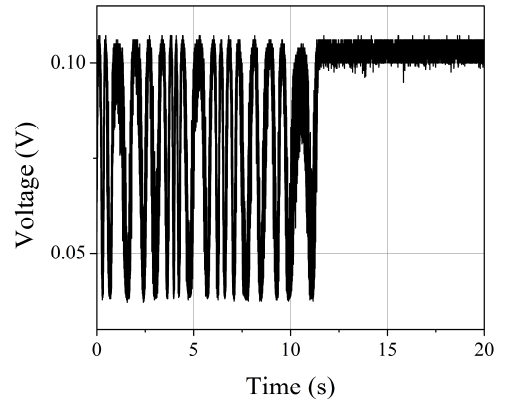


Figure 2. Interference signal of the DFG idler waves, fluctuating between destructive and constructive interference when CBC is inactive and stabilizing on a constructive interference state when phase-locking is active.

Time-averaged combining efficiency is excellent: the residual phase error is $\lambda/28$ rms for the idler wave.

This experiment is the proof that CBC of continuous wave DFG using indirect phase control is feasible, hence proving that OPO CBC is also feasible as the nonlinear process involved in both cases is the same: parametric amplification.

The main difference between SHG CBC and DFG CBC is that simultaneous phase locking that has been proved feasible for SHG combination [3], cannot be achieved so easily when combining non-degenerate three-wave mixing frequency

converters [5].

Even if seeded, the optical path difference between the two signal channels induces a phase difference that is not compensated for, and the signal waves are not phase-locked simultaneously when the idler waves are.

4. CHALLENGES OF OPO CBC

The main drawback of DFG processes is their extremely low efficiency. For instance, pumping the DFG modules of the CBC experiments with 15 W at 1.064 μm , the power generated at 3.4 μm was only a few milliwatts. But breaking records in terms of power was not the goal of the DFG CBC experiment previously presented.

OPO CBC is much more interesting as placing a parametric amplifier in a cavity can significantly increase the efficiency of the parametric process. OPOs have higher efficiencies than DFGs (10 - 20 % efficiency can be achieved in OPOs) and demonstrating experimentally that CBC of OPO is feasible could offer an interesting option to power scale frequency converters.

However, an OPO places the parametric amplifier inside a cavity that adds some phase constraints to the process and indirect phase control of an OPO is not as simple as for the DFG modules.

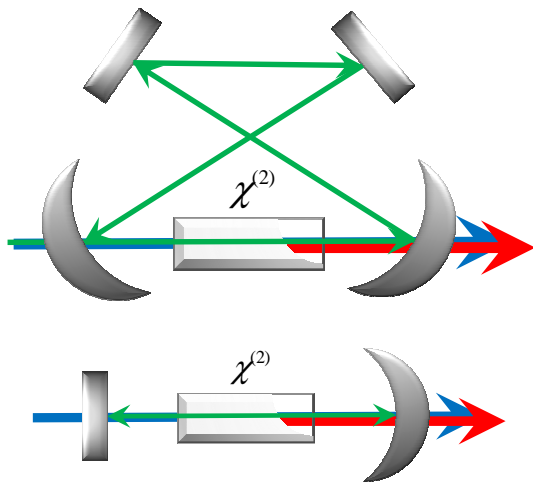


Figure 3. Cavity architectures of continuous wave OPOs.

There are two main architectures for a continuous wave OPO, as can be seen in figure 3: ring and linear cavities can be used.

A ring cavity generally offers lower threshold and the first challenge of developing cw OPOs for CBC was to lower as much as possible their threshold.

Lowering the threshold too much is not suitable either, as a cw OPO becomes unstable in terms of emitted power when pumped more than 3 times its threshold.

Analytical estimates of continuous wave OPOs are available in the literature [6].

Optimizing the design of the cavity in terms of pump, signal and idler beams overlap and minimizing the threshold simultaneously, different

configurations with a theoretical threshold around 10 W were chosen and tested.

Another configuration of nested cavity doubly resonant OPO (NesCOPO [7]) was also optimized with a threshold that could be as low as a few hundred milliwatts and fine wavelength tuning capability.

Combining these OPOs could lead to interesting sources that could be power scaled by increasing the number of OPOs combined, and benefit from the fine tuning capability of one of them.

The last challenge to overcome is the coupling between two feedback loops that is required by OPO CBC.

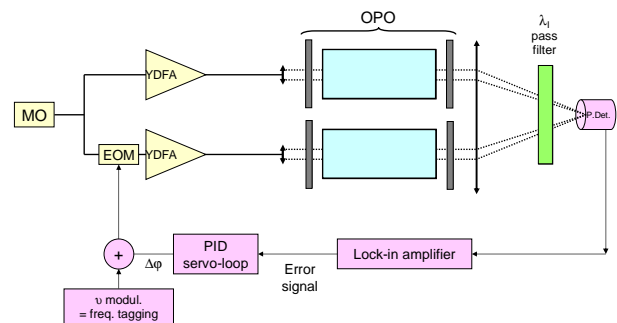


Figure 4. Schematics of the basic architecture required to combine two OPOs.

As can be seen in figure 4, the phase control feedback loop has of course to be operated to perform efficient OPO CBC. But simultaneously, one has to guarantee that the idler wavelength amplified in both OPO cavities is the same. That can only be achieved by adding a second feedback loop controlling the cavity length. Operating both feedback loops simultaneously is the main challenge of OPO CBC.

5. OPO CBC EXPERIMENTS

We set up an OPO CBC experiment and we are testing the double feedback loop control to check if OPO CBC is practically feasible.

The experimental setup is similar to the one presented in figure 4: two singly resonant OPOs with low threshold pumped by two 15 - 20 W emitting Yb: fiber amplifiers are combined.

Simultaneous control of the phase of one of the pumps and of the cavity length of one of the OPOs is tested.

First results of these experiments will be presented during the conference.

6. CONCLUSION AND FUTURE WORK

In this paper, the challenges of applying coherent combining by active phase control to much more powerful frequency converters, optical parametric oscillators (OPO), is presented. Optimizing the OPO threshold and coupling two different feedbacks are the main challenges in designing an optimal experiment.

We also described the experimental demonstration of OPO CBC we are now testing.

The first results of this experiment will be presented during the conference.

7. ACKNOWLEDGEMENTS

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