# Femtosecond OPO Based on Orientation-Patterned Gallium Phosphide (OP-GaP)

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**Abstract:** We report the first femtosecond OP-GaP based OPO suitable for ultrabroadband frequency comb generation. The 15-dB bandwidth of 2.6-4.2 μm was obtained from a compact low-threshold (14 mW) OPO pumped by 85-fs Er-fiber laser.
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## 1. Introduction

Zincblende semiconductors such as GaAs and GaP are promising candidates for nonlinear optical frequency downconversion because of their large second-order nonlinearity and infrared transparency beyond 10 μm. Broadband femtosecond mid-IR OPO sources using orientation-patterned gallium arsenide (OP-GaAs) pumped at 2 μm [1] and 2.35 μm [2] were previously demonstrated. However, when the pump wavelength is shorter than 1.7 μm, GaAs shows strong two-photon absorption accompanied by severe losses due to free carriers. Because of its larger bandgap, GaP allows to avoid this short-wavelength limitation and utilize common pump sources such as Er-doped (1.5 μm) or Yb-doped (1 μm) fiber lasers. The first parametric oscillation in the OP-GaP was demonstrated using nanosecond pulses at 2 μm [3] and 1 μm [4]. Here we report on the first femtosecond OP-GaP based OPO.

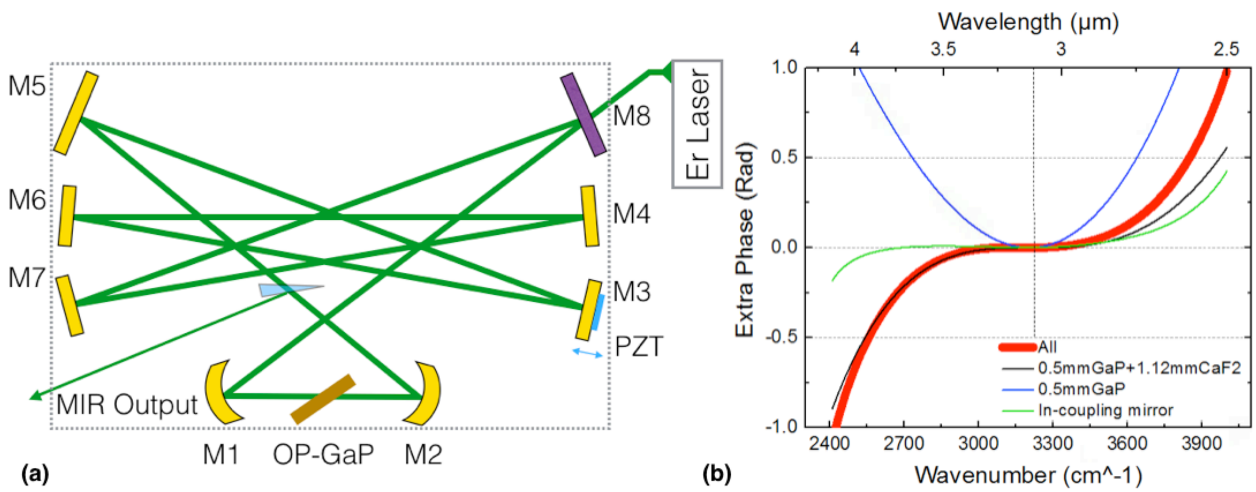


**Fig. 1.** a) Schematic of the OP-GaP OPO pumped by an Er-fiber laser. b) Computed extra phase accumulated per cavity round trip due to the dispersion of 0.5-mm OP-GaP, in-coupling mirror, and $CaF_2$, which was added for dispersion compensation.

## 2. Experiment

The OP-GaP, manufactured by BAE Systems, was grown by a combination of molecular beam epitaxy (MBE) and low-pressure hydride vapor phase hyper epitaxy (HVPE). The 500-μm thick OP-GaP had a quasi-phase-matched (QPM) period of 46.5 μm. It was not anti-reflection coated, but was placed at the Brewster angle to minimize the reflection. Moreover, the OP-GaP crystal was cut such that the laser beam inside the crystal was normal to the QPM layers. The OPO cavity was composed of a dielectric in-coupling mirror M8 with high transmission (>85%) for pump laser and high reflection (>95%) for 2.4 to 4.2 μm and seven gold-coated mirrors, two of which (M1 and M2) were parabolic with an off-axis angle of 30˚ and radius of curvature in the apex R=30 mm, and the other five (M3-M7) were flat. This folded design was very compact and allowed fast cavity purging with dry air to a humidity of

2%. A 1.12-mm thick $CaF_2$ wedge was used for dispersion compensation. The pump was a 1560-nm mode-locked Er-fiber laser from Toptica Photonics (average power 300 mW, repetition frequency 80 MHz, pulse duration 85 fs).

## 3. Results

The OPO operated in a doubly-resonant near-degenerate mode. The lowest pump threshold was 14 mW (with intracavity loss estimated to be 11%). Besides dispersion compensation, the $CaF_2$ wedge acted as an outcoupler. With 1.6 % outcoupling that we used for measurements, the threshold was 16 mW. We tuned the cavity length using a PZT actuator attached to one gold-coated mirror (M3). The OPO can operate at several discrete round trip cavity lengths with a constant separation ~1.56 µm (approximately the pump center wavelength) [5]. The first two peaks, corresponding to the degenerate operation, yield broad continuous spectra, extending from 2400 $cm^{-1}$ (4.2 µm) to 3850 $cm^{-1}$ (2.6 µm), as seen in the 2D spectrum measured by a scanning monochromator and shown in Fig. 2a. Considering all the peaks, the low frequency limitation is due to high extra cavity phase. The high frequency limitation comes from the reflection bandwidth of the in-coupling dielectric mirror, whose reflectivity drops significantly below 2.6 µm. The instantaneous output spectra of the OPO were measured using a spectrum analyzer (Bristol Instruments, Inc.). The broadest continuous spectrum observed corresponded to the second cavity detuning peak, as shown in Fig. 2b. The spectral dips around 3750 $cm^{-1}$ (2.7 µm) are the water vapor absorption lines caused by the residual $H_2O$ molecules in the cavity.

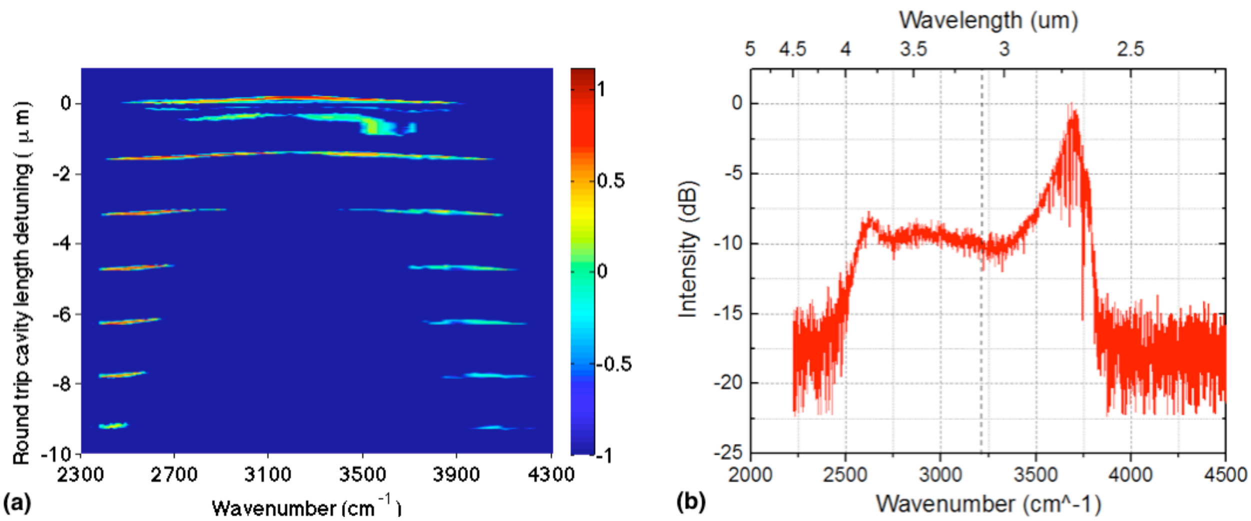


**Fig. 2.** a) 2D color intensity plot of spectra as the round trip cavity length is detuned with 2% humidity after purging with dry air. b) The broadest degenerate spectra of OPO. Dotted line is OPO degeneracy.

## 4. Conclusion

A low-threshold (14 mW) femtosecond OPO was demonstrated based on the novel OP-GaP nonlinear optical material, which overcomes the short-wavelength pump limitation of the OP-GaAs. As compared to periodically poled lithium niobate (PPLN) OPO at similar conditions [5], we have got broader instantaneous spectrum, thanks to higher parametric gain bandwidth and better mid-IR transparency of GaP. To further broaden the spectrum, we plan to use mirrors with broader reflectivity range that will also be chirped for dispersion compensation.

## References

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