# High efficiency pump-enhanced difference frequency generation for mid-IR communications

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# High Efficiency Pump-Enhanced Difference Frequency Generation for Mid-IR Communications

Liam Flannigan[1], Ali Atwi[1], Tyler Kashak[1], Daniel Poitras[2], and Chang-qing Xu[1]
[1]*Department of Engineering Physics, McMaster University, Hamilton, Ontario, L8S 4L8*
[2]*Advanced Electronics and Photonics Research Center, National Research Council Canada, Ottawa, Ontario, K1A 0R6*
flannilg@mcmaster.ca

***Abstract*—We report a compact difference frequency generation (DFG) intracavity structure emitting at 3.43 microns with greater than 100 mW output power. The device consists of a diode-pumped Nd:$YVO_4$ cavity providing the 1064 nm pump light, and a C-band EDFA signal beam coupled into the cavity via a dichroic mirror. The pump and signal are combined in a 50 mm PPLN to generate mid-infrared light via quasi phase matching. The proof of principle prototype was previously published, but we have since improved the total output power and have a more developed prototype ready for professional packaging. We also present the theory and simulation work that led to the improvements and discuss future possible optimizations using insights from the modelling.**

***Keywords—difference frequency generation, optical communication, DPSS laser, mid-infrared***

## I. Introduction

There has been a surge of interest in technologies that facilitate free space optical communication, both for terrestrial and satellite-to-ground links. This is largely due to the advantages of optical communication over radio-band communication, such as increased security, higher bandwidth, less stringent regulation of frequency bands, and smaller payloads [1], [2]. One promising avenue is communication in the mid-infrared (3-5 microns) atmospheric transmission window, which offers reduced scintillation and atmospheric scattering over the short-wave infrared (0.8-1.7 microns) [3]. Typically, the upper limit for transmitter power for low earth orbit is hundreds of mW to watt-level power to guarantee a stable link [4]. Our group has previously demonstrated a proof-of-principle intracavity DFG structure capable of modulation at gigabit speeds emitting in the MWIR by utilizing periodically poled lithium niobate (PPLN) [5]. We have since made several significant improvements including a packaged prototype, higher output power, and improved efficiency, which we present here alongside a brief discussion of the modelling that led to these changes.

## II. Results

The experimental setup is shown below as a block diagram in Fig. 1:

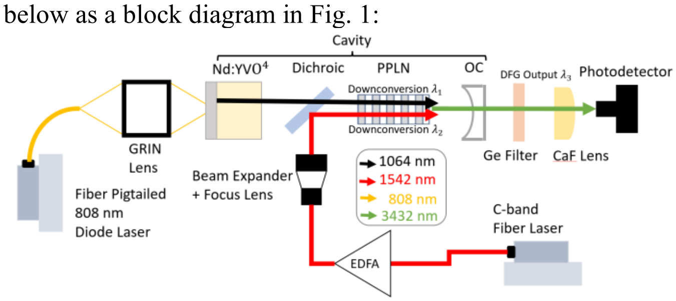


Fig. 1. Experimental schematic of the pump-enhanced DFG. The C-band laser can be tuned from 1525-1560 nm, and 1529 nm was selected as this allowed near-room temperature operation with the period of the PPLN [5].

And the packaged prototype can be viewed in Fig. 2, made from aluminum with dimensions 8 x 3.75 x 3 cm.

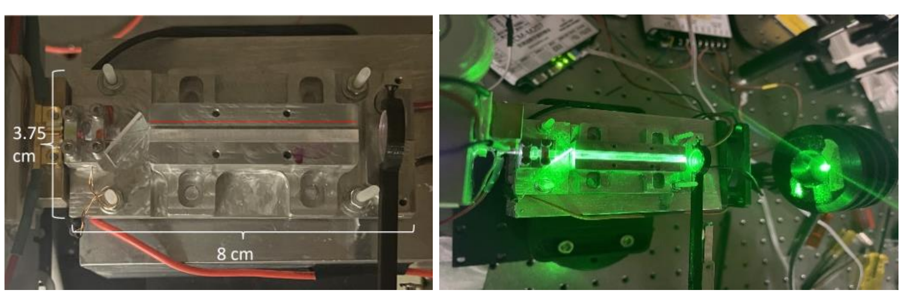


Fig. 2. Packaged prototype of the DFG laser. The green light is from second harmonic generation (SHG) due to the tens of watts of 1064 nm present in the cavity, despite the period of the PPLN being unoptimized for SHG. This does not significantly impact the efficiency as the conversion rate is low.

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The maximum output power from the packaged prototype was 109 mW of 3.43 micron power for 4.5 W 808 nm pump power and watt-level C-band power, checked after a Ge window to filter the leaking 808 nm, 1064 nm, and C-band power. The laser can also be modulated via direct or external modulation of the C-band source, limited only by the modulation bandwidth of the chosen C-band laser.

## II. Discussion

This packaged prototype represents a significant improvement over our previously reported proof of principle design, which had a maximum output power of 31 mW in the mid-IR with a corresponding black box efficiency of 2.2%$W^{-1}$ [5]. However, there is still significant room for improvement according to theory. First, the C-band power needs to be investigated further, as a significant amount of leaking power was amplified spontaneous emission far from the optimal phase matching wavelength, so the total measured power was not representative of the effective input power for DFG. Once a suitable bandpass filter has been acquired for the C-band source, the true EDFA power can be measured and a new black box efficiency can be recorded. Given the power increase over the previous iteration, however, we are confident that we have improved efficiency by optimizing the overlap, which we will discuss now.

The second major issue with the proof-of-principle design was the overlap between the signal and pump beams in the PPLN, as the pump beam was significantly larger than the signal beam. While our proof-of-principle design utilized a fixed 5x beam expander, we have since switched to a 1-4X zoom beam expander to fine-tune the signal overlap and compare with theory. According to the theoretical framework presented by Guha et al., the confocal parameter of our pump was ~0.22 while the signal was >2, which is a poor overlap [6]. As the cavity design restrained the pump size, the easier solution was to increase the spot size of the signal to improve overlap. As expected, the new optimal performance was attained at a zoom of 2.5X, representing a significant increase in the overlap of our beams and an increase in overall efficiency. The exact beam sizes were confirmed using ABCD matrix modelling for the pump, and Zemax for the signal beam. If we assume that we can maintain the current efficiency while increasing the signal power for a fixed (no/minimal depletion) pump power, we can extrapolate that it should be possible to increase the output power to the hundreds of mW as seen in Fig. 3, given a powerful enough C-band laser. We hope to demonstrate this while also attempting other avenues for further increasing efficiency in the future.

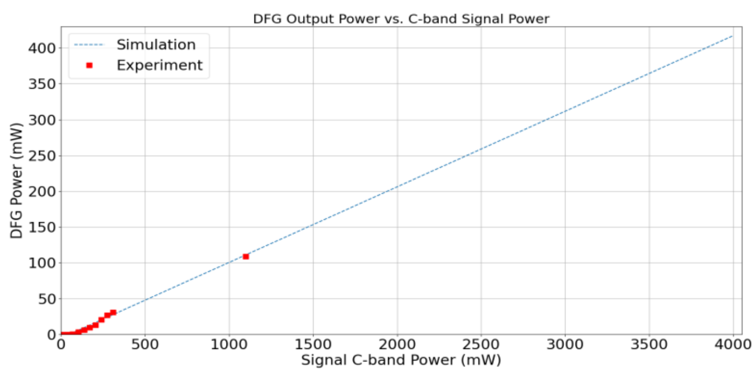


Fig. 3. Experimental data is represented by the red squares, while the blue dotted line is a line of best fit, assuming the efficiency stays constant at higher powers.

## III. Conclusion

We have reported a compact DFG intracavity structure with >100 mW output power and the highest black-box efficiency for a bulk intracavity device. Through modelling work, significant improvements have been made to the efficiency, and a prototype for future professional packaging was developed. Finally, avenues for further improvement were identified, suggesting the possibility of hundreds of mW to watt-level output power in the future.

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