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Power Scaling of Dispersive Wave Generation using Higher Order Modes

(Invited paper)

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***Abstract*—We demonstrate power-scaling of nonlinear frequency conversion in fibres via dispersive wave generation using higher order modes. By pumping in the $LP_{0,m}$ modes at 1030 nm we show wavelength selectability between 550 and 800 nm with pulse energies up to tens of nJ.**

***Index Terms*—Fibre optics, nonlinear optics, frequency conversion**

I. INTRODUCTION

Frequency conversion based on nonlinear phenomena is an established technique for extending the spectral coverage of laser sources where no gain media are available. Among these phenomena, dispersive wave generation (DWG) in an optical fibre allows to convert energy to a wavelength that is established by a phase matching equation, arbitrarily far from the pump wavelength, and with low noise. Our modelling predicts a potential for power-scaling of DWG using the higher order modes (HOMs) of a fibre [1]. We confirm this experimentally by using a single HOM in a large-core silica-based step-index-fibre (SIF), allowing to both obtain anomalous dispersion at 1030 nm, where Yb fibre lasers are available, and increase the core area and hence the power level. The spatial coherence of the output will allow to reconvert the mode at the fibre output to a gaussian beam with high efficiency up to approximately 80 % [2]. Lastly, we discuss the limitations and prospects for further development of this technique.

II. EXPERIMENTAL RESULTS

A. Commercially available fibres

We first demonstrate the power scaling principle in a $d = 50\mu m$ core diameter step-index fibre from Thorlabs Inc., with $NA = 0.22$. We focus on the $LP_{0,m}$ modes, which in a weakly-guiding SIF are truncated Bessel modes in the core region ($\psi(r,\phi) = J_0(\kappa r)$), as they can be excited by using an axicon with coupling efficiencies up to 85%. The modes with $m = 8, 9, 10$ experience anomalous dispersion at the pump wavelength, and their dispersive waves are in the $700-800nm$ range. We pump with 150 fs pulses of energies $E_p \approx 100nJ$, and obtain DWG conversion efficiencies $\eta_{DW} \sim 5-10\%$. Previous work in our group used a single mode photonic crystal fibre, obtaining up to 130 pJ at 612 nm [3]. Compared to this we here observe a two orders of magnitude increase in the DWG pulse energy, although the wavelengths in this work are closer to the pump wavelength, hence the conversion efficiency is expected to be higher. There also exists a larger version of this fibre, with core diameter $d = 105\mu m$, which we are testing to obtain a further power scaling.

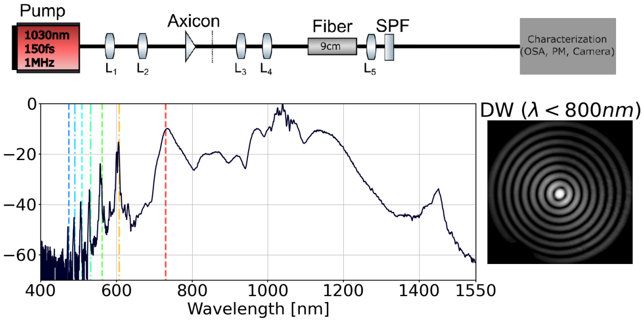

Fig. 1. Top: setup for excitation and characterization of DWG in HOMs. Bottom: exemplary spectrum. The pump mode in the $d = 50\mu m$ core diameter fibre is $LP_{0,9}$, pump energy is $E_p = 143nJ$ and the resulting DWG pulse energy is $11.6nJ$. The vertical lines show the predicted phase matched wavelengths, with a cascade of intermodal weaker dispersive waves following the main intramodal one at $\lambda \sim 730nm$. The image shows the shortpassed mode profile.

B. Specialty high NA fibre

To further push the converted pulse towards shorter wavelengths, we used a large NA (0.34) SIF with core diameter $d \approx 50\mu m$, which guides up to the $LP_{0,15}$ mode. All modes above $LP_{0,7}$ have anomalous dispersion at 1030 nm. To avoid damage of the input facet, the maximum amount of power that can be injected in the fibre decreases with increasing mode order. This is because the intensity of center spot, which increases with mode order, causes dielectric damage. The (deterministic, single pulse) damage threshold is at a fluence of about 10nJ/μm^2 [4], which is consistent with our estimates of the peak fluence in the center spot of the pattern. Furthermore, the dispersion parameter also increases with mode order, further weakening the nonlinearity. Eventually, this limited the power of their dispersive waves, and prevented

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us to observe DWG in the $m = 14, 15$ modes. Figure 2 recaps the results we obtained in the fibres we tested.

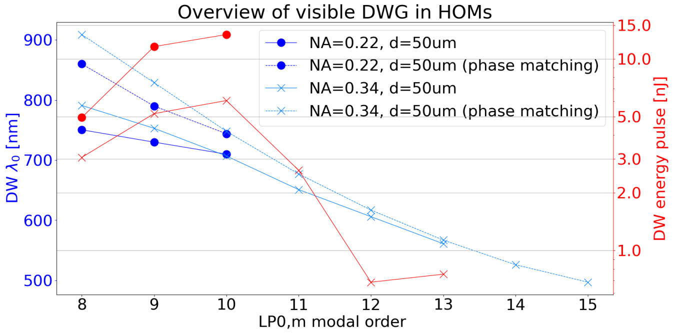

Fig. 2. DWG power and wavelength; same markers are used for the same fibre. Note that the phase matching curves we report are calculated without considering the nonlinear phase term of the pump, hence it is expected that the actual wavelength will be blue-shifted. Not all data points are optimized in terms of fibre length and input coupling conditions, so the reported energies are not always the maximum achievable.

III. OPTIMIZING THE CHOICE OF THE MODES

To mitigate the power limitations we encountered, we propose two approaches. The first one is controlling the fibre size, and the second one is moving to higher angular orders, such as the $LP_{1,m}$ modes. In a single step index fibre with a certain Δn, the phase matched DWG wavelength decreases with increasing mode order. In general, if the fibre size is increased(decreased), increasing(decreasing) the modal order accordingly will keep the target wavelength constant. With this principle in mind, figure 3 shows that increasing the fibre size will reduce the maximum soliton number of the input pulse if facet damage is to be avoided, $N_S \propto \sqrt{P_0/DA_{eff}}$, although at a larger power level. N_S determines the strength and noise level of the frequency conversion process. Efficient generation of a single spectral peak with low noise typically requires N_S ~10-15, albeit with some variations. Since the conversion efficiency η_{DWG} is mainly dependent on the pulse compression process, it will be approximately constant when scaling the fiber as described above, and the input power scaling will translate into an output power scaling.

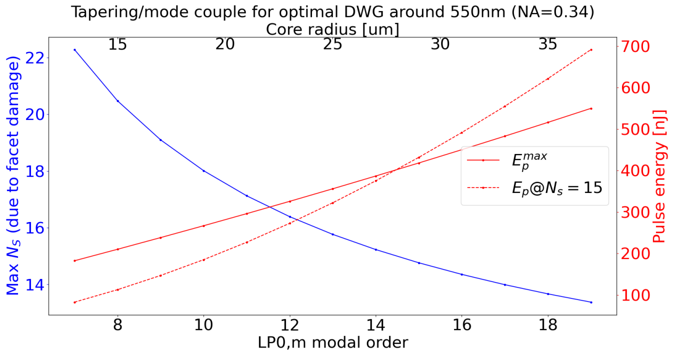

Fig. 3. Trade-off between power and soliton number in fibres of different sizes, but with the same DWG target wavelength.

A different approach is to look at different classes of modes, as for example the $LP_{1,m}$. Figure 4 reports a comparison of the $LP_{n,m}$ modes with $n = 0, 1, 2$ in the high NA fibre we tested. These modes have comparable dispersion and linear stability (evaluated using the n_{eff} splitting from their nearest neighbor, but not included here), but increasing the angular order will better distribute the power on the facet, as seen in their A_{eff}, allowing to scale the power by a factor ~ 3 compared to the $LP_{0,m}$, while keeping the same input soliton number. Coupling in and out of these modes will increase the complexity of the setup, as a single axicon will not be sufficient anymore. We have obtained initial promising results by combining a simple binary phase plate with an axicon. The typical length for the fibres we are using is very short (10 cm), and experimentally we have not observed mode rotation, so phase plates are a viable option for output beam reconversion.

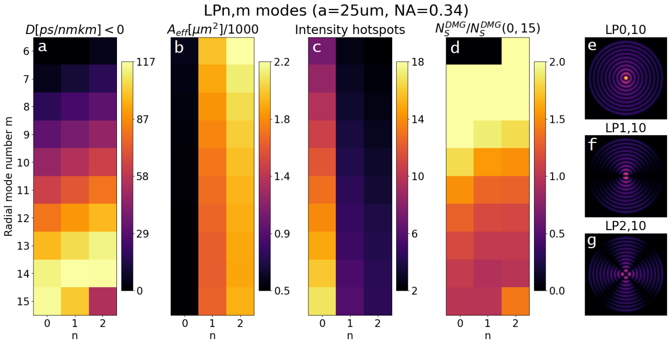

Fig. 4. Comparison of first angular mode orders. a+b) factors in the soliton number $N_S \propto \sqrt{P_0/DA_{eff}}$, c) maximum intensity , d) maximum soliton number. e-g) exemplary intensity profiles.

IV. CONCLUSIONS

We have demonstrated power scaling in-fibre nonlinearities by pumping in a single higher-order mode of a large-core step-index fibre. We observe a two orders of magnitude scaling with respect to comparable single-mode results. We find that the main limitation of this technique is optical damage at the input facet of the fibre, and we investigate possible mitigation techniques for this.

ACKNOWLEDGMENTS

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