Single-parameter optimization of femtosecond supercontinuum generation in bulk YAG using effective filament length

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Optimizing supercontinuum generation (SCG) in bulk media requires multi-parameter tuning of pump power, numerical aperture and crystal length[1]. Here we show that these variables can be largely reduced to an effective filament length, L_{eff} defined as the separation between the first and second nonlinear foci in nonlinear medium. Using 180 fs, 1030 nm pulses, we find that the infrared spectral bandwidth scales nearly linearly with L_{eff} over the experimentally accessible range. An analytic estimate of L_{eff} therefore provides a guideline for predicting and optimizing the SCG bandwidth for given input pulse.

I. The spatial evolution of filaments in bulk dielectrics

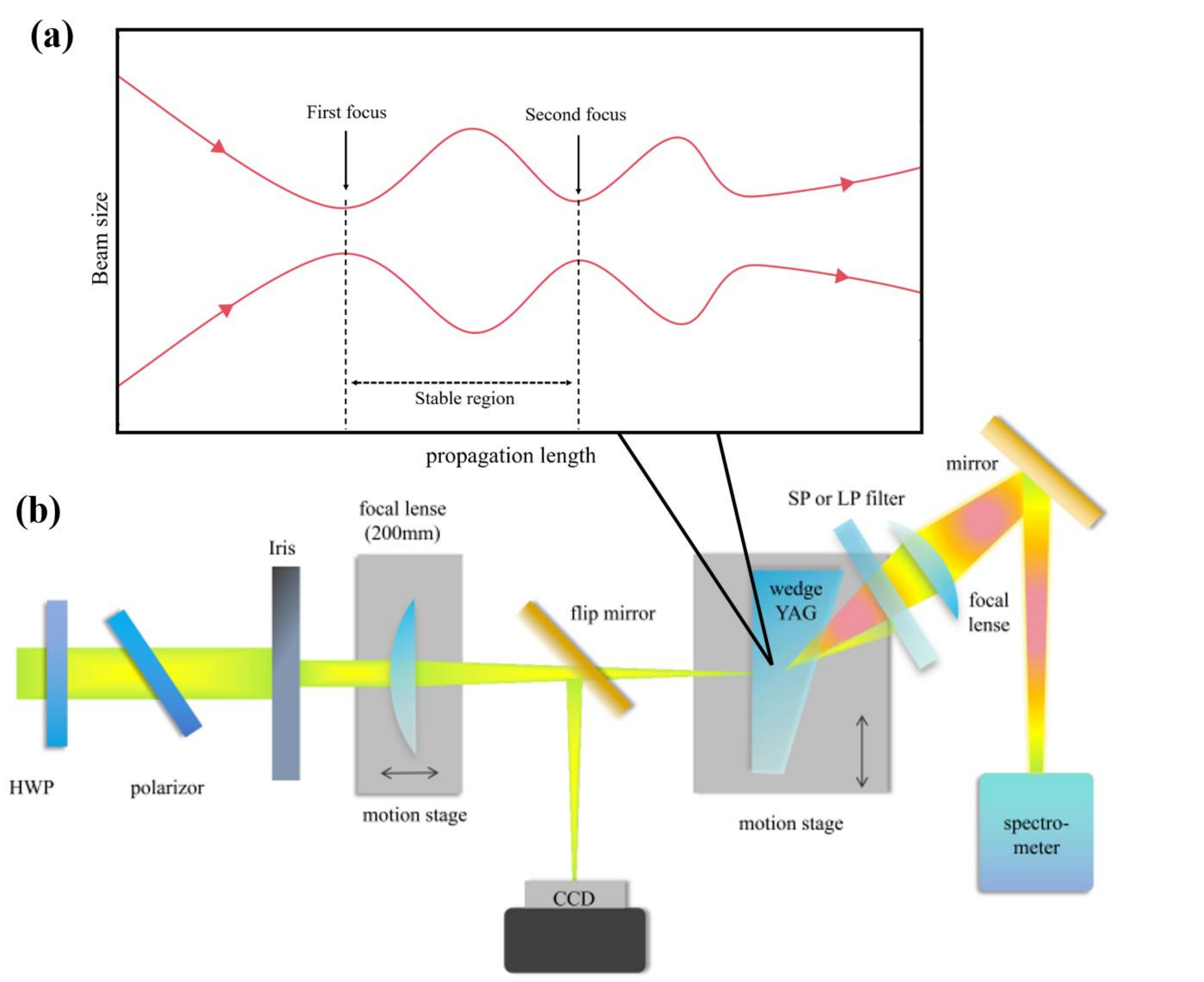

Fig. 1: Experimental setup for wedged YAG scanning. a, The spatial evolution of filaments in bulk media, exhibiting a focusing–defocusing–focusing cycle due to the competition of the Kerr effect and multiphoton absorption. The supercontinuum shows stability between the first focus and the second in existing studies. **b,** Experimental setup for wedged YAG scanning. Half wave plate and polarizer control the input power, an adjustable iris controls the numerical aperture, the motion stage moves vertically towards the beam direction to change crystal thickness. A CCD was placed at the same distance as that from the YAG to the flip mirror, allowing real-time observation of the beam profile on the front surface of the crystal.

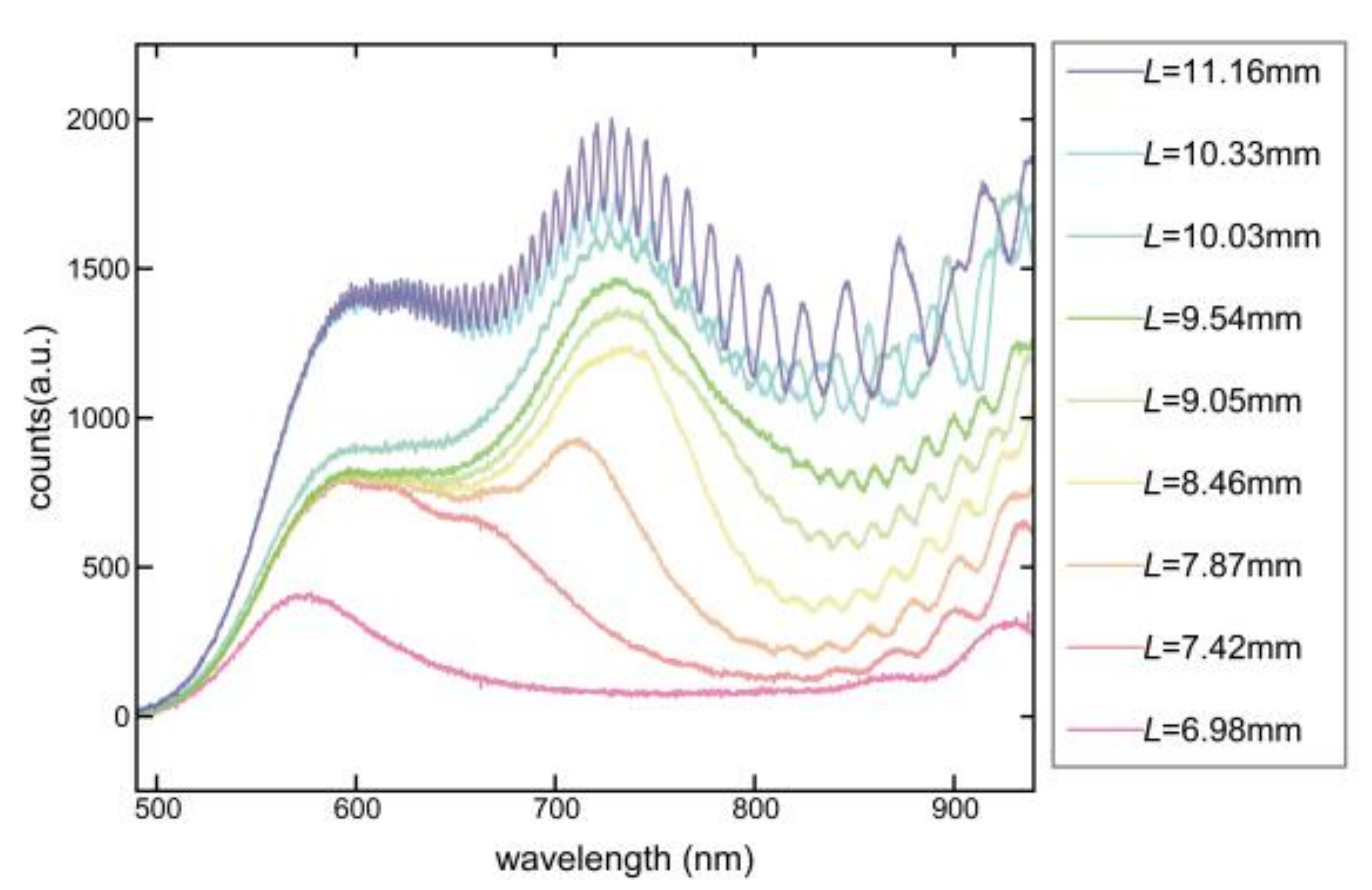

Fig. 2: Supercontinuum spectra of thickness scanning. Self-phase modulation broadens the spectrum, and this broadening increases continuously with propagation length until saturation[2]. Once the second focus begins to form, periodic modulation appears in the spectrum, induces extreme sensitivity to energy fluctuations and becomes unsuitable for application as a stable light source.

II. L_{eff} as a governing parameter in SCG optimization

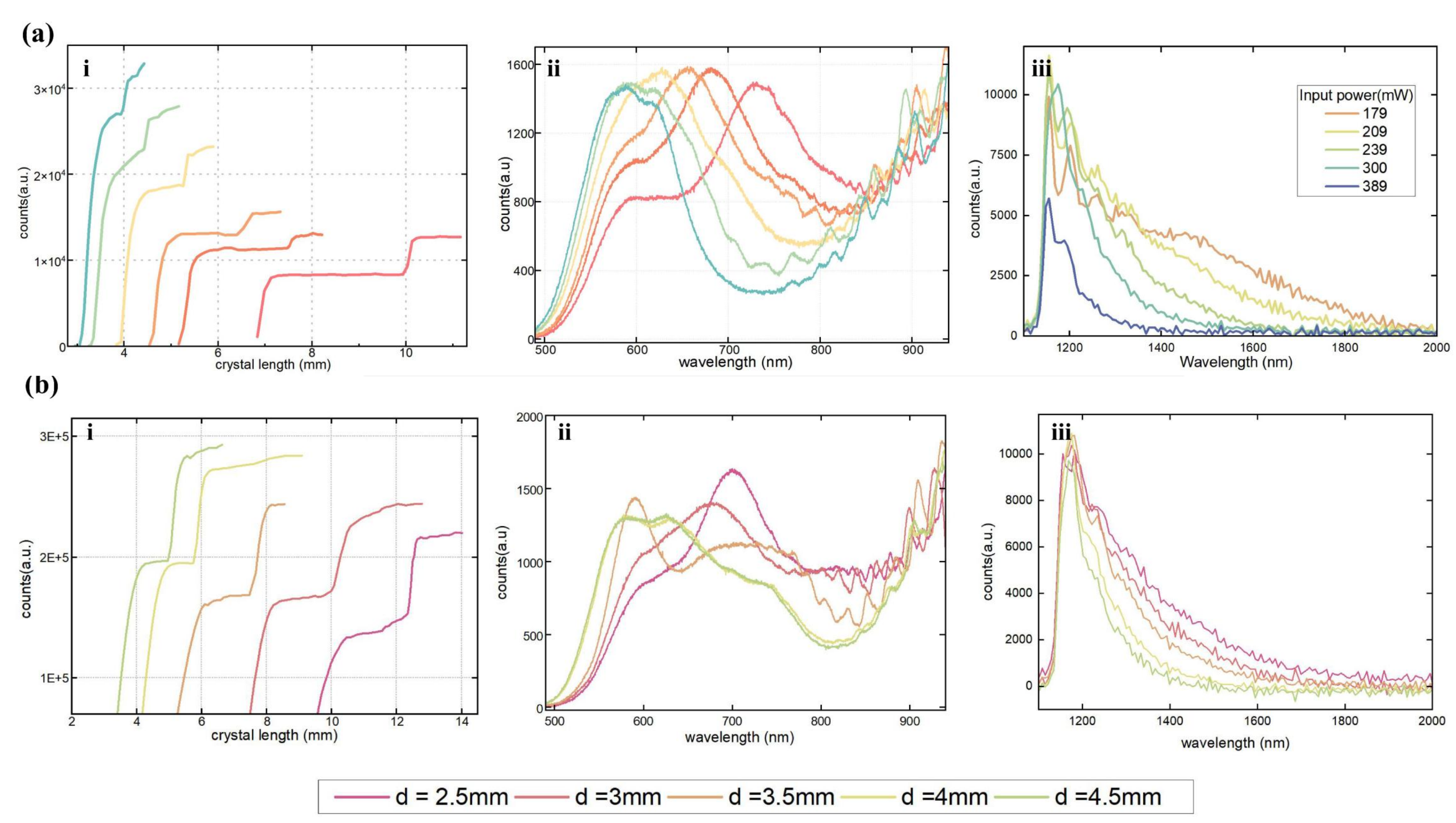

Fig. 3: Pump power and numerical aperture dependence of supercontinuum. a(i), a(ii), a(iii), Change pump power to collect the visible and infrared supercontinuum spectra, higher power result in frequency shift and narrower bandwidth, while the effective length decreases accordingly. **b(i), b(ii), b(iii),** Change numerical aperture to collect the visible and infrared supercontinuum spectra, a wider bandwidth appears as the numerical aperture decreases, indicating the necessity of loose focusing condition in supercontinuum generation.

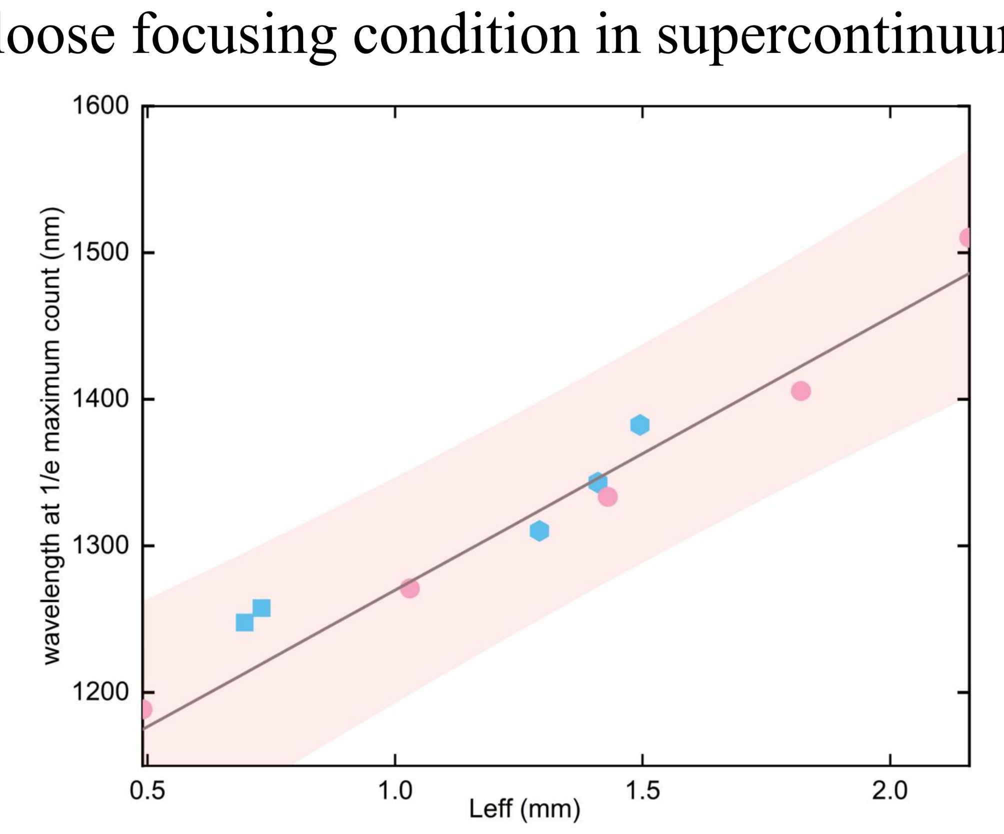

Fig. 4: Linear correlation between effective length and spectral broadening. Effective length is calculated from Lugovoi's formula[3], vertical axis represents the spectral broadening. Pink and blue dots are power and NA dependent measurements, respectively, the solid line is a linear fit with a 95% prediction band. For various combinations of parameters in different dimensions, the correlation between L_{eff} and the broadening consistently exhibits a highly linear pattern, demonstrating the feasibility of using L_{eff} as a single parameter in SCG optimization.

III. Conclusion

We propose the effective length as a single governing parameter to guide the optimization of SCG, and demonstrate that it is fully reasonable to encapsulate the multi-parameter space with this single parameter. Our study provides a simple and effective guideline for SCG in bulk crystals within various optical module designs. By evaluating the effective length, it establishes a more concise framework and greatly simplifies the preliminary design work.

Reference:

1. Jiucheng Chen, Hengyuan Xiao, Tianliang Zhang, Siqin Ding, Jianfei Hua, and Wei Lu, "Energy stability of supercontinuum via femtosecond filamentation in sapphire," Opt. Express 33, 53428-53435 (2025)

2. Lukáš Roškot, Ondřej Novák, Bianka Csanaková, Jiří Mužík, Martin Smrž, Michal Jelínek, and Tomáš Mocek, "Importance of crystal length on the stability of a picosecond supercontinuum generated in undoped YAG," J. Opt. Soc. Am. B 40, 1391-1397 (2023)

3. V N Lugovoĭ and A M Prokhorov 1974 Sov. Phys. Usp. 16 658