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Conversion of Mode-Locked States within an Optical Cavity

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Locking longitudinal modes of an optical resonator results in the generation of short laser pulses, whereas, locking its transverse modes results in a beam rapidly scanning the transverse plane. Common schemes for generating such transverse mode-locked beams involve off-axis pumping of a gain medium inside a resonator [1–3]. Which modes, and to what extent, are involved in the locking process has been analyzed [1] and controlled by simple means, e.g., by limiting the highest mode order with a slit [1], transversely displacing the pump spot [2] or varying the pump power [3]. Here, we present the generation of transverse mode-locked beams with improved control over the modal amplitudes by longitudinal to transversal mode conversion. We also consider the inverse process of transverse to longitudinal mode conversion to generate temporal pulses when injecting a spatially oscillating beam.

A simple longitudinal mode-locked beam can, for example, be generated by modulating a single frequency laser beam in amplitude yielding at least two sidebands with a frequency separation $\Delta\nu_L$ to the carrier ν_0 (see Fig. 1a). However, the transverse modes of a cavity are frequency shifted by $\Delta\nu_T$ due to their specific Gouy phase shifts. Then, if the transverse mode spacing matches the modulation frequency ($\Delta\nu_T = \Delta\nu_L$), not only the carrier but also each sideband frequency can excite a separate transverse mode within the cavity and will be transmitted. As the incident longitudinal modes, that is carrier and the sidebands, are in phase with each other, so are the excited transverse modes, resulting in a transverse mode-locked output beam.

This scheme can be reversed and should result in conversion of a transverse mode-locked input, i.e. a scanning beam, to a longitudinal mode-locked output, i.e. a temporal pulsed beam.

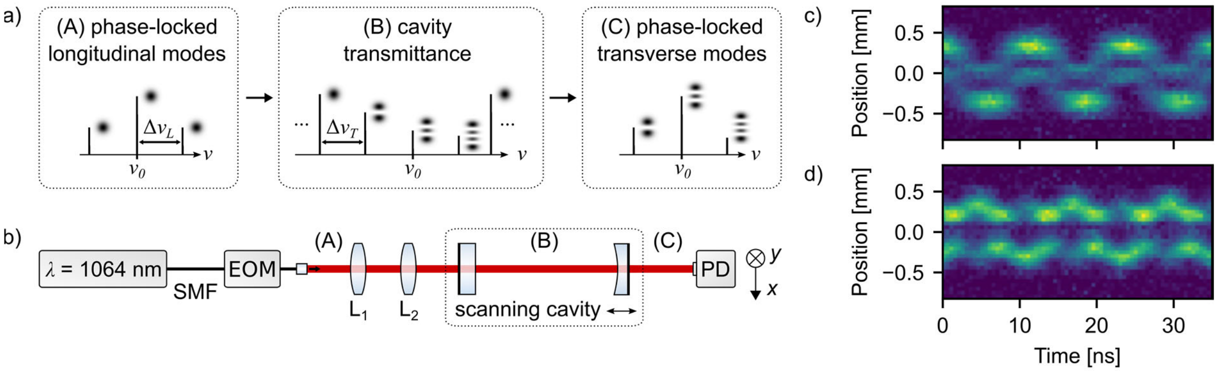

Fig. 1 Schematic of the conversion from a longitudinal mode-locked state into a transverse mode-locked state in a). Experimental realization in b). Measured resulting spatiotemporal oscillations with $\Delta\nu_T$ = 80 MHz for two different sets of modal amplitudes in c) and d). Single mode fiber (SMF), electro-optic modulator (EOM), lens (L) and photodiode (PD).

For a proof-of-principle experiment, with a sinusoidal modulation signal two sidebands were imprinted on a longitudinal mode which enabled the generation of mode-locked beams comprised of a superposition of three transverse modes. The Hermite-Gaussian (HG) modes $HG_{0,1}$, $HG_{0,2}$ and $HG_{0,3}$ were brought into resonance with the incident frequencies by tuning the cavity length appropriately. The measured spatiotemporal distributions (see Fig. 1c and d) have clearly visible oscillation periods being inverse to the transverse mode spacing (1/80 MHz = 12.5 ns) characteristic for transverse mode-locked beams. In this scheme the amplitude modulation signal acting upon the output beam of a single frequency laser allows to control the amplitudes of the generated sidebands, which affects how strongly each transverse mode is excited. This made it possible to switch between a $0.24\times HG_{0,1} + 0.60\times HG_{0,2} + 0.15\times HG_{0,3}$ superposition (see Fig. 1c) to a configuration with modal amplitudes of 0.57, 0.15 and 0.28, respectively (see Fig. 1d) and thereby alter the resulting spatiotemporal oscillation.

In conclusion, we demonstrated the generation of transverse mode-locked beams by conversion from a longitudinal mode-locked beam. This allows to not only control which transverse modes are excited, but also to influence their amplitudes and the resulting spatiotemporal oscillation.

References

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