Fiber-based laser systems for 3G detectors: State-of-the-art and outlook

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The waveguide feature of optical fibers brings many benefits to laser systems, e.g. a high single-pass gain with excellent beam quality and good thermal robustness. In addition, monolithic all-fiber systems allow for compact, turn-key and user-friendly lasers. As a result, fiber-based laser systems are a promising alternative to bulky and complex solid-state lasers and amplifiers as they are currently used in all 2G detectors. However, the waveguide feature also brings new challenges into play, e.g. non-linear effects (in particular stimulated Brillouin scattering (SBS), i.e. stimulated scattering on acoustic phonons) due to long effective interaction lengths.

We present the current status of our fiber-based laser development program in Hannover (LZH and AEI) for 3G detectors. We developed a 200 W fiber amplifier engineering prototype at 1064 nm (based on a 25 µm large-mode area (LMA) fiber) with an optical performance that is either on par or even significantly better than the aLIGO solid-state laser system. For example, the beam quality i.e. the TEM_{00} content is better than 94% at all output power levels with a polarization extinction ratio (PER) of more than 18 dB. The amplifier does not add any frequency/phase noise, provides a relative intensity noise (RIN) comparable to the aLIGO laser and is free of SBS because of an active SBS suppression scheme. Due to its monolithic setup the fiber amplifier provides (to the best of our knowledge) the best pointing noise performance that has ever been measured for GWD lasers. At the time of writing, the amplifier has already been operated in a long-term test for more than two weeks without any degradation and this particular test will continue during the coming months. The design of our fiber amplifier prototype is modular with four different modules: (i) seed in-coupling with actuators for external stabilization, (ii) pre-amplification, (iii) free-space Faraday isolation & monitoring and (iv) high-power amplification. All components and fibers are commercially available (COTS) and the modular design allows for simple maintenance and plug-&-play replacement of modules. Currently, we are working on a second prototype at 1064 nm with minor technical upgrades. Once both systems are operational we will perform experiments regarding the differential phase noise and the coherent combination for further power scaling.

In addition to our work at 1064 nm, we also developed a 100 W fiber amplifier prototype at 1556 nm for cryogenic (silicon-based) 3G detectors. The system was thoroughly characterized in terms of beam quality, frequency and intensity noise and the polarization performance (although the particular fiber was not polarization maintaining (PM)). At the time of writing we are setting up an advanced system with PM fibers which will provide as much pump power as will be required to scale the output power to 200 W.

In addition to our aforementioned prototypes we recently also focused on novel numerical simulation tools that help us to predict and optimize the performance of the amplifiers. For example, amplifier systems at 1556 nm must be pumped off-resonantly to suppress parasitic lasing effects due to unsaturated gain and stimulated spontaneous emission (ASE). The optimization of such concepts requires detailed knowledge about the amplifier performance. Recently, we also started to study the time-dependent performance of fiber amplifiers, in particular to study transient and potentially harmful parasitic lasing (pulsing) effects in case of a sudden seed laser failure.

Besides our work on prototypes based on standard step-index fibers we recently also achieved very promising results with a specialty fiber design, namely chirally-coupled-core (CCC or 3C) fibers. For the first time, we were able to develop a monolithic hybrid system based on an active CCC fiber with a 35µm core and passive single-mode step-index fibers. So far, this system was tested up to 50W of output power (still not limited by pump power or any other effect) and demonstrated an outstanding (considering the large size of the core) TEM_{00} content of more than 97%.