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AMPLIFICATION PROPERTIES OF RAMAN FIBER AMPLIFIERS FOR NARROWBAND SINGLE FREQUENCY SOURCES

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INTRODUCTION:

There are a number of applications where Single Frequency (SF) narrowband seed sources need to be amplified while maintaining spectral purity and with a minimum amount of added noise. Laser cooling of atoms often requires high power sources with very specific frequencies matching atomic transitions to create atomic clouds of super cooled matter. Often, we receive questions regarding the evolution of single-frequency (SF) signal properties during amplification. For example,

- how the linewidth and both the intensity and phase noise of a single-frequency input signal change during amplification?
- how the RFA output power and signal-to-noise ratio depend on the input seed power?
- what spectral bandwidth can be covered by RFA and VRFA?
- and what are the seed source requirements?

This paper covers optical properties of Raman Fiber Amplifiers (RFA) and Visible Raman Fiber Amplifiers (VRFA) with Second Harmonic Generator (SHG).

RFA-SF AND VRFA-SF – PRINCIPLE OF OPERATION, FEATURES AND AVAILABLE MODELS

The RFA-SF-series is a polarization-maintaining optical RFA for amplification of a narrowband CW signal from an external SF source. It features two amplification stages separated by a mid-stage optical isolator, input and output signal power monitors and a backward-travelling Stimulated Brillouin Scattering (SBS) power monitor (Fig. 1). The RFA is pumped by the linearly-polarized output of a high-power fiber laser which is injected at the output end of the RFA and propagates through the RFA in the direction opposite to that of the signal. The pump optical frequency is upshifted with respect to the signal frequency by approximately 12 to 15 THz, corresponding to the Raman shift in silica-based Ge-doped fibers. Thus, as the signal propagates through the RFA, it experiences optical gain via Stimulated Raman Scattering (SRS).

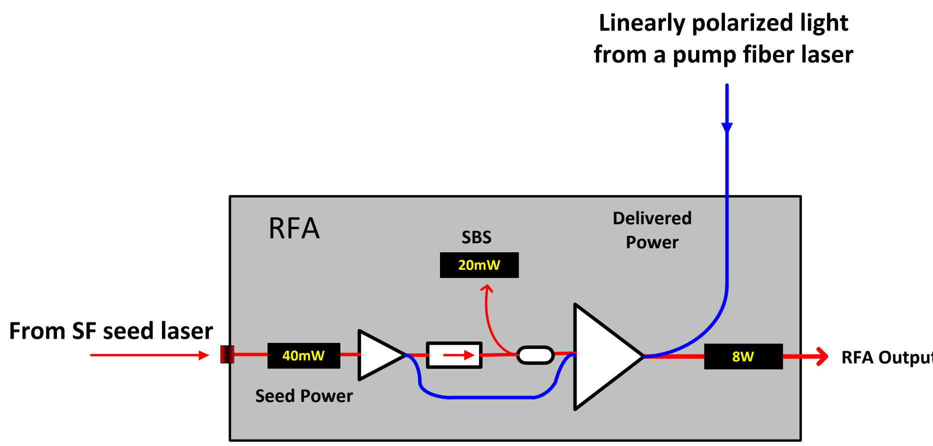

Fig. 1. Diagram of Raman Fiber Amplifier (RFA-SF series).

The pump light from the pump module is guided to the RFA by a polarization-maintaining pump delivery fiber, protected by a stainless-steel conduit. In the VRFA-SF series, an SHG module is added to convert the near-infrared output wavelength from the RFA to the visible region (Fig. 2). The pump module microcontroller monitors parameters of RFA via the RFA monitor cable. It also provides active power stabilization of the SHG output power and temperature stabilization of the SHG crystal through the SHG control cable.

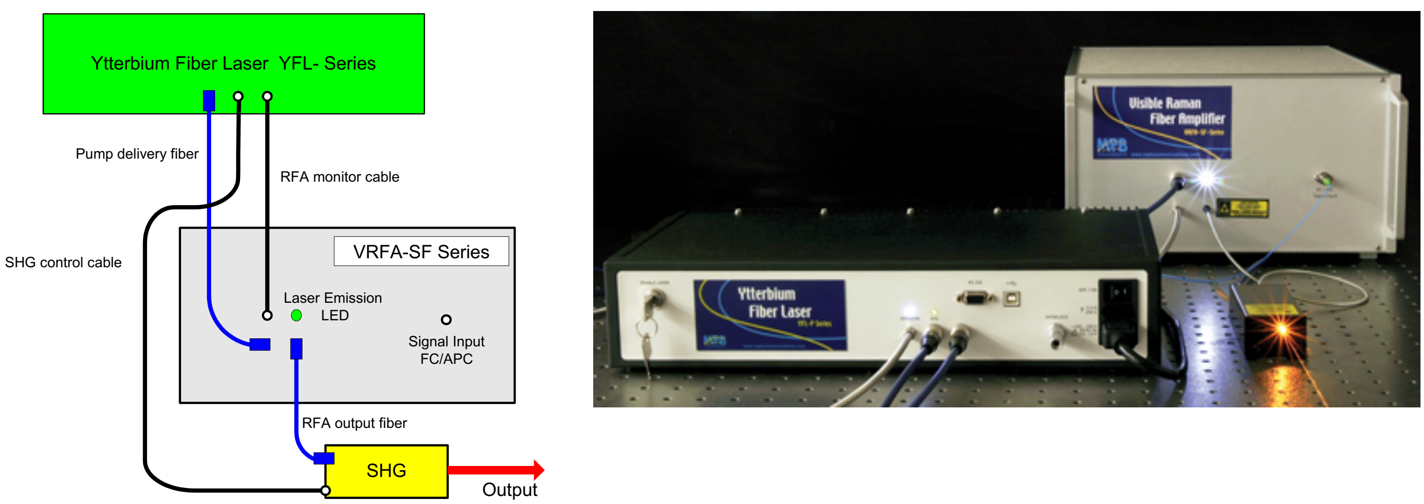

Fig. 2. Diagram and photograph of Raman Fiber Amplifier with SHG (VRFA-SF series) pumped by Ytterbium Fiber Laser.

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RFA OUTPUT POWER, SIGNAL-TO-AMPLIFIED SPONTANEOUS EMISSION RATIO AND ITS DEPENDENCE ON THE INPUT SEED POWER.

Typically, SF seed sources such as DFB laser diodes (LD) or external cavity LDs emit CW optical power in the range of 5 to 50 mW. The RFA-SF design makes it possible to amplify such relatively weak and extremely narrow SF source outputs to 8-15 Watts, as shown in a typical power vs pump LD current chart (Fig. 3). The RFA can operate in either Automatic Current Control (ACC) or Automatic Power Control Mode (APC). In APC mode the output power is maintained constant by a closed feed back loop connecting an output power monitor and an LD current driver. In the case of a VRFA, the SHG output power is maintained constant in APC mode using a built-in SHG power monitor.

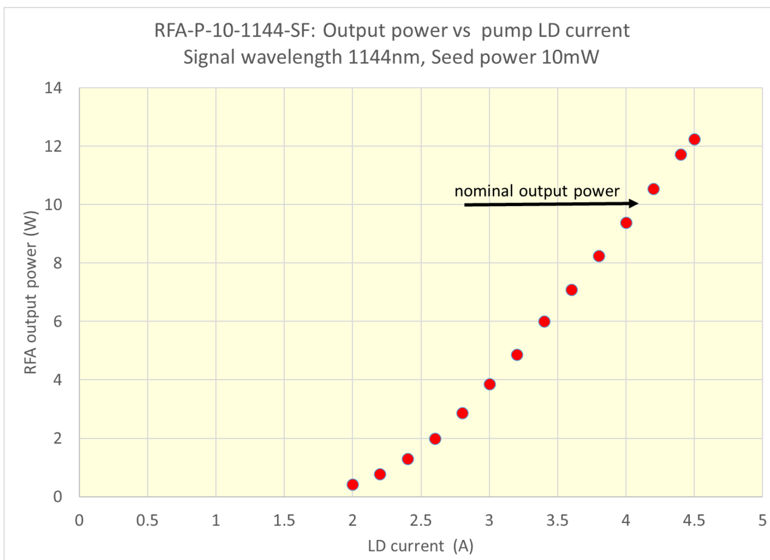

Fig. 3. Output power of 1144-nm RFA as function of pump LD current.

When the input signal is relatively strong, it saturates the gain of RFA, making it possible to extract more power (Fig. 4). That is why we recommend the seed power to be 20 mW or more.

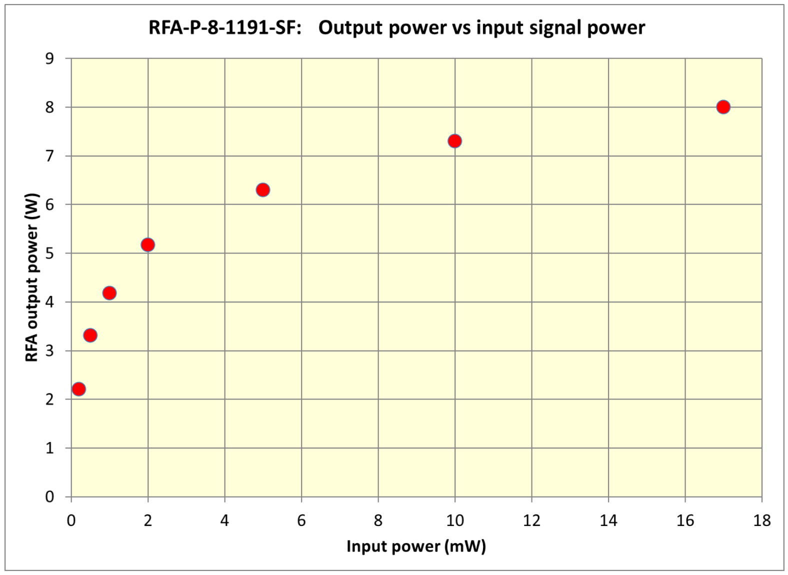

Fig. 4. RFA output power as a function of the seed input power.

When a SF signal is amplified in an RFA, ASE added to the signal manifests itself as a relatively broad pedestal under an otherwise very narrow signal. A stronger input signal provides a better Signal-to-ASE ratio at the RFA output (Fig. 5). In situations when a strong seed power can't be provided, a seed power of 10 mW should still be sufficient to achieve a desired output power, albeit with a slightly lower Signal-to-ASE ratio. If the signal power is strong, ≥20 mW, the ASE power at the RFA output is 60-65 dB lower than the signal when measured with a 0.01-nm resolution. The bandwidth of ASE is of the order of 15 nm, but it becomes much narrower at the SHG output. Essentially the SHG works as a narrowband nonlinear filter, effectively converting mainly the strong narrowband signal.

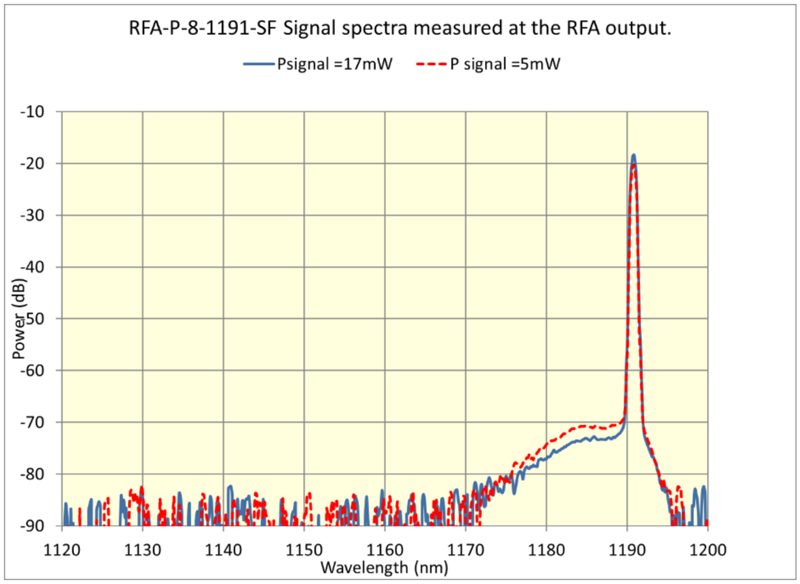

Fig. 5. Output spectra of at the output of 8-W 1191-nm RFA measured with 0.5-nm resolution when the seed input power was set to 5 mW and 17 mW. The Signal-to-ASE ratio is 50 dB and 55 dB, respectively.

Each RFA and VRFA system is equipped with an input signal power monitor. The monitor not only allows one to observe the launched seed power, but also provides for automatic shutdown if the seed power drops below a minimum pre-set power level.

AMPLIFICATION BANDWIDTH OF RFA AND VRFA, SHG TEMPERATURE TUNING.

The Amplification bandwidth of RFAs depends on the SRS bandwidth of the amplification fiber being used, pump wavelength and transmission spectra of other optical components of the RFA optical train. A typical dependence of RFA output power as a function of a seed wavelength is shown in Fig. 6. At a fixed LD pump current, the FWHM bandwidth is of the order of 15 nm. A reduction of the RFA power at wavelengths away from the optimal can be compensated, at least partially within this band, by increasing the pump LD current. For example, a 10-W RFA amplifier optimized for operation at 1146 nm can still provide 10 W at 1142 nm or 1150 nm if the LD pump current is increased from 4 A to 4.3 A (Fig. 6).

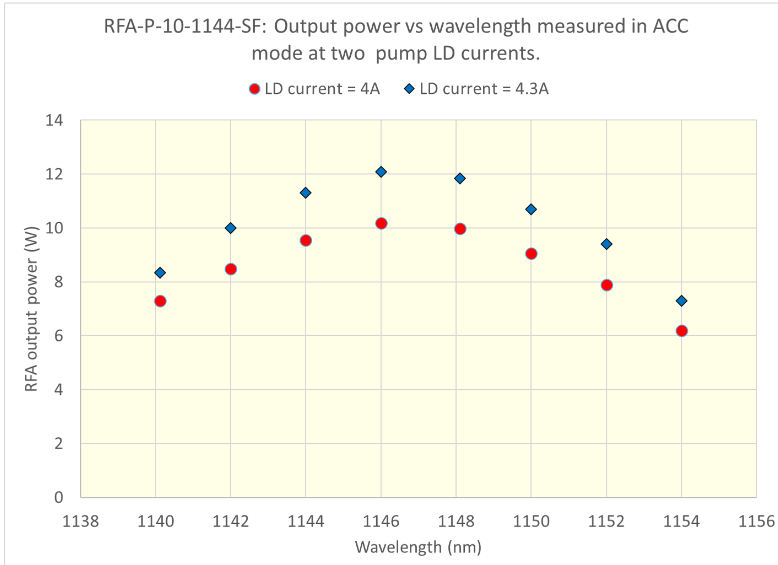

Fig. 6. RFA output power as function of the seed laser wavelength. Seed power 11 mW.

In VRFAs, the signal tuning range is much narrower, since it is restricted by the ability of the periodically-polled SHG crystal to be Quasy Phase Matched (QPM) with the seed frequency. We provide a very wide choice of VRFAs, each optimized for operation at a very particular wavelength. For example, VRFA-P-2000-589-SF, VRFA-P-2000-652-SF and VRFA-P-1500-671-SF are optimized for operation around 589, 652 and 671 nm, respectively. Each system allows for some seed tuning around the nominal wavelength by adjusting the temperature of the SHG crystal. It always important to adjust the SHG temperature when operating the system for the first time and every time after the seed frequency is changed. In addition, it is advisable to tune the SHG temperature periodically to ensure the best SHG conversion efficiency and therefore, the minimum operational pump LD current. It is always important to run the VRFA system in ACC mode while optimizing the SHG temperature, please refer to VRFA-SF user's manual (*MPBC DOC-04787*) for RSHG tuning procedure. A typical tuning rate is 0.5 nm per 10 °C as shown in Fig. 7. Typically, the crystal's TEC operational temperature range is 30 to 70 °C, thus limiting the seed tuning range to 2 nm in the visible band.

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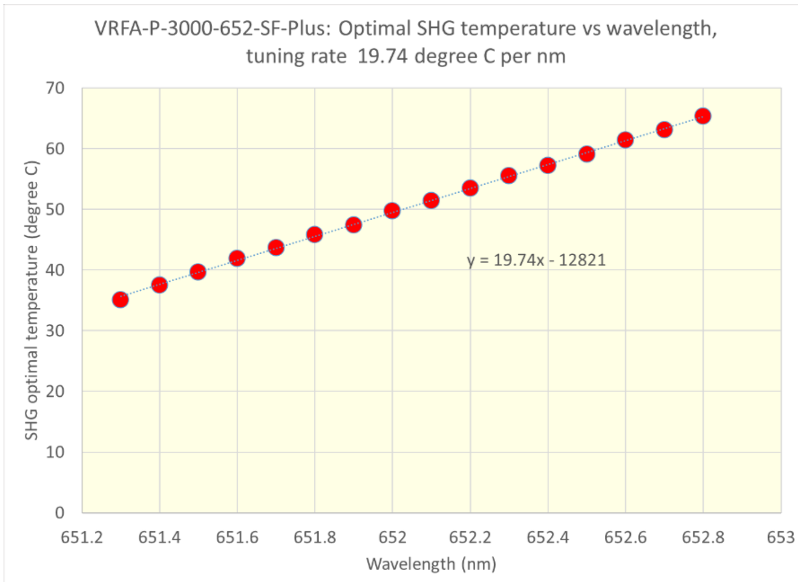

Fig. 7. SHG crystal optimal temperature as function of the seed wavelength measured in VRFA-P-3000-652-SF.

RFA INTENSITY NOISE.

In addition to ASE, the signal picks up intensity noise originating from the intensity noise of the pump fiber laser while it propagates in the RFA fiber. The Relative Intensity Noise (RIN) spectrum measured at the output of 1266-nm 8-W RFA (Fig. 8) reveals that the main noise frequency components are located below 2 MHz.

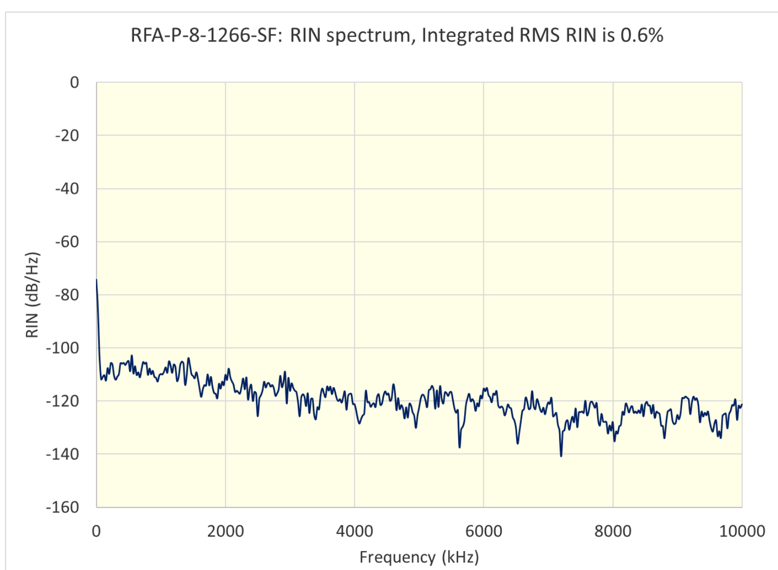

Fig. 8 RIN spectrum measured at the output of 8-W 1266-nm RFA. Integrated across 10MHz RMS RIN is in the order of 0.6%.

PHASE NOISE AND LINEWIDTH.

Any seed signal picks up some phase noise while propagating in the RFA fiber. We've conducted a comparison study of the phase noise of an extremely narrow linewidth SF fiber laser, before and after amplification. A Fabry-Perot interferometer was used to convert the source frequency fluctuations into amplitude fluctuations which were then in turn measured by an RF spectrum analyzer (Fig. 9)

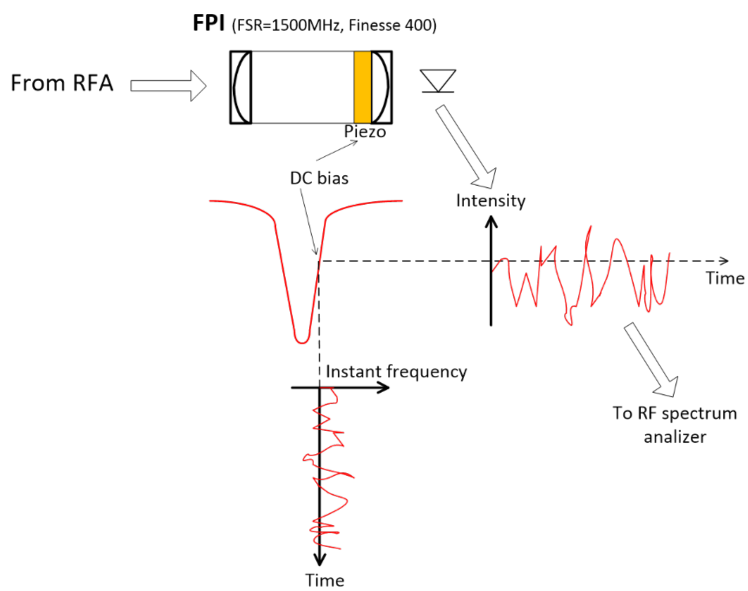

Fig. 9. Frequency noise measurement set-up.

The spectral distribution of the frequency noise density of the SF seed measured before and after amplification (Fig. 10) reveals that the seed frequency noise is extremely small and localized at very low frequencies. During amplification the signal pick up some phase noise, mainly at frequencies below 2 kHz.

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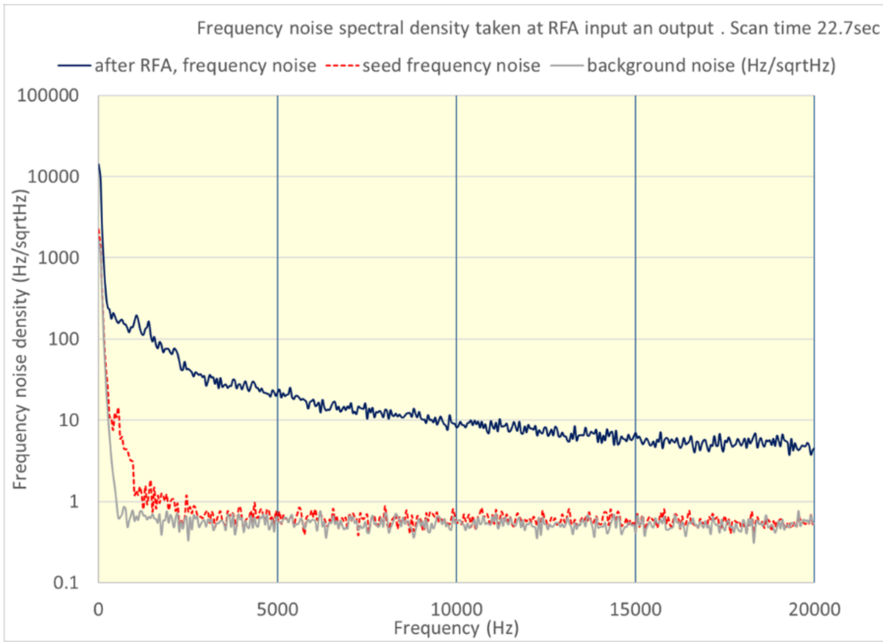

Fig. 10. Frequency noise measurement set-up.

By integrating the spectral distribution of the frequency spectral noise density, we have estimated the linewidth of the seed laser before and after amplification. As one can see from Fig. 11, the seed estimated linewidth is about 700 Hz. After amplification the integrated linewidth becomes 7 kHz. Interestingly, the main frequency noise contributions come at frequencies below 1500 kHz, higher frequency components are so small that they do not contribute to the overall linewidth.

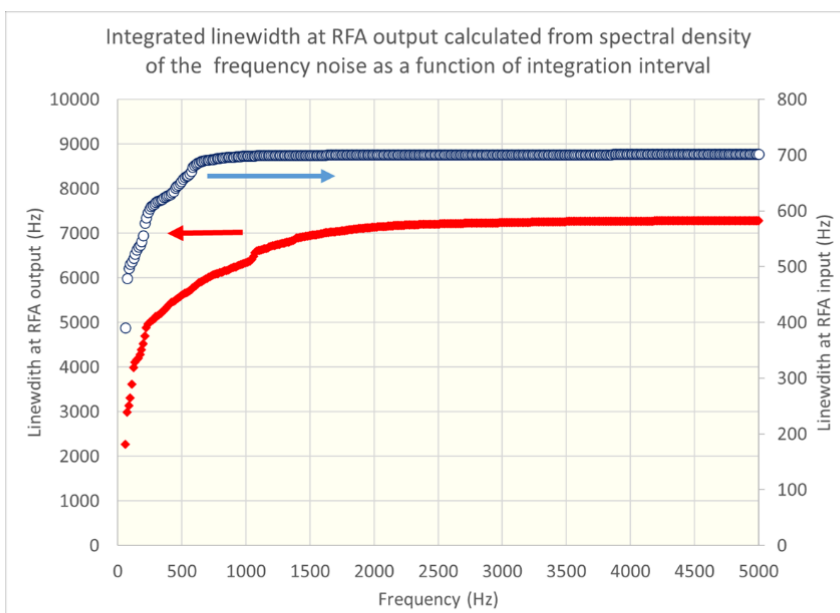

Fig. 11 Integrated spectral linewidth of the seed before and after amplification.

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In addition to the frequency noise analyses, we have conducted a self-heterodyne experiment using a Mach-Zehnder fiber interferometer with an arm difference of 35 km. As can be seen from the RF spectrum shown in Fig. 12, the beat noise linewidth after amplification is only few kHz. That might be somewhat underestimated due to insufficient time delay of the interferometer, which is also evident from periodic oscillatory modulation of the RFA spectra background. Such oscillations also confirm that the coherence length after amplification remains much longer than 35 km of optical fiber used.

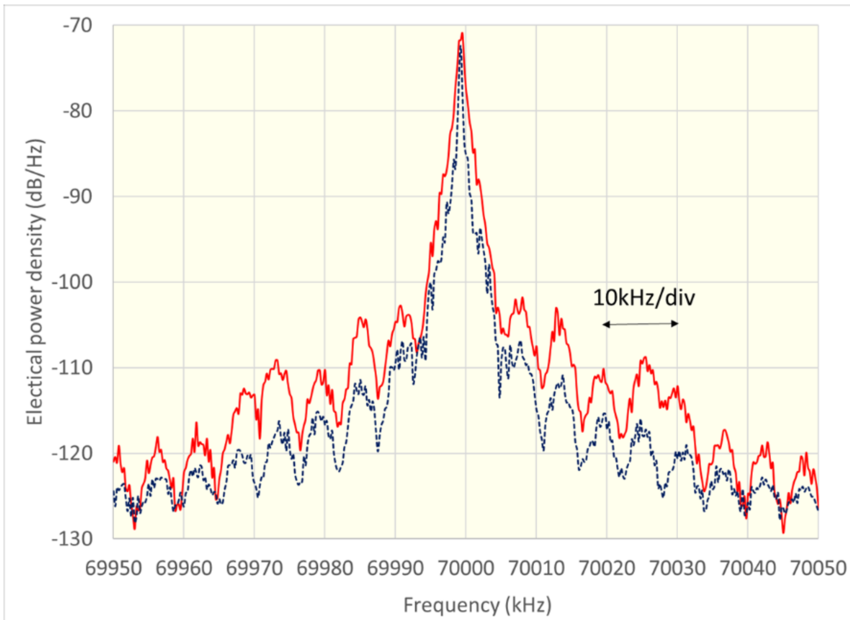

Fig. 12. Beat note measured after 35km unbalanced interferometer before and after amplification.

BEAM QUALITY AND POLARIZATION.

All RFAs are made of single-mode polarization-maintaining (PM) fibers. As such, they provide a true diffraction-limited output beam with a polarization vector matching the key of the output connector, corresponding to the slow axis of a PM fiber. A seed source should be equipped with a PM fiber output terminated with an FC/APC connector and have a polarization vector aligned with the slow axis and a Polarization Extinction Ratio (PER) of 20 dB or more. RFAs do not amplify the light launched into the fast axis. A poor PER and/or improper orientation the seed polarization vector might result in undesirable RFA output power variations and therefore have to be avoided.

In VRFAs, a diffraction-limited beam is focused into a bulk nonlinear crystal and then collimated. As a result, they emit a diffraction-limited beam with a divergence determined by the beam waist diameter of the collimated beam, nominally 1mm in diameter. The beam quality remains excellent over a wide range of optical powers, with the beam quality M^2 <1.1 as shown in Fig. 13.

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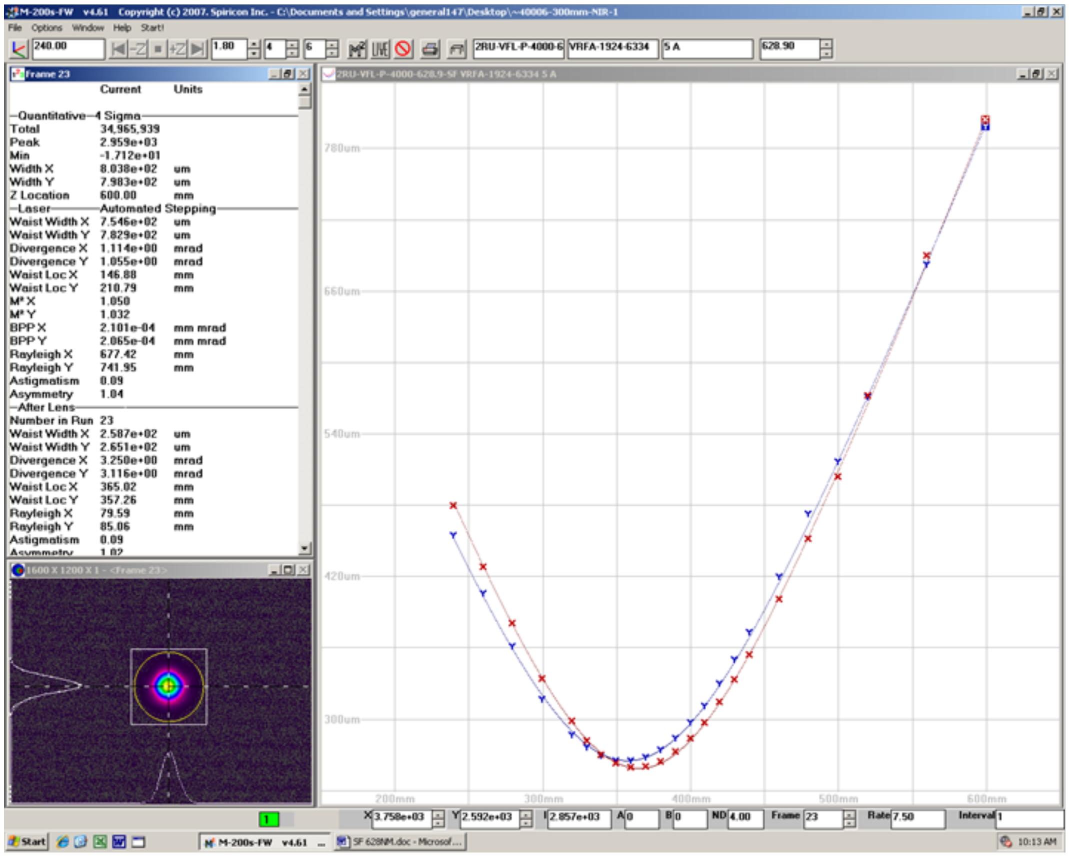

Fig. 13. Beam evolution along propagation axis taken at the output 4-W 628nm VRFA reveals M^2 of 1.05 and 1.02 in X and Y axii.

SHGs in the VRFA-SF-Plus family have, in addition to the main visible beam, a second infrared (IR) beam output (Fig. 14). This light comes from a dichroic filter separating the visible and remaining IR light after the second harmonic crystal. Depending on the model, the power in this second output can be in the range of a few Watts to 10 Watts. The IR beam is also close to diffraction limited, but not collimated.

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Fig. 14. VRFA-SF-Plus series in addition to visible beam, additional IR high power output located at the side of the SHG is provided.

PROTECTION FROM SBS AND BACK REFLECTIONS

(V)RFAs are equipped with a backward-travelling SBS power monitor as shown in Fig. 1. It serves to protect the system in the event of a backward signal power exceeding a pre-set power level. The RFA output fiber is terminated with an FC/APC AR-coated connector with a built-in Mode Field Diameter (MFD) expander, so as to eliminate any reflection from the connector and reduce the power density on its AR coated surface. RFAs do not have output isolators and therefore it is important to avoid any substantial back reflection from customer's external optics being coupled back into the RFA output fiber. The amplifier emits a diffraction limited beam with a typical MFD of 18 20 μm. The connector is intended to be used with customer AR coated optics, such as a beam collimator, and cannot be mated with any other fiber connector due to the MFD mismatch and the very high power. A customer should always use proper AR-coated optical elements and avoid right-angle beam incidence to optical surfaces. Often, a small tilt of optical elements is sufficient to minimize reflected light from being coupled back into RFA fiber.

VRFAs emit a collimated beam with a typical beam diameter of 1 mm. They are equipped with IR blocking filters at their output, thus providing additional protection for RFA optical trains. In the case of VRFAs, customer optics need to be AR-coated for the proper visible wavelength.

CONCLUSION REMARKS

Raman Fiber Amplifiers and Visible Raman Fiber Amplifiers are excellent means for scientific and industrial applications where high-power single-frequency laser sources are needed. Moreover, RFAs preserve linear polarization and spectral properties of very narrow single-

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frequency sources and allow fine frequency tuning to very particular frequencies of interest. Both RFAs and VRFAs provide diffraction limited beams, an important feature for very tight focusing and manipulation when needed. A great variety of infrared and visible wavelengths can be covered due to the nature of the SRS process. Please try to challenge us with a new wavelength which is not yet available on the market, most likely we can help. And don't hesitate to ask questions concerning points which are not clear or not covered in this paper.