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INVESTIGATIONS OF A DUAL SEEDED 1178 NM RAMAN LASER SYSTEM

Leanne Henry, et al.

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14. ABSTRACT

The leakage of 1121 nm power from a resonator cavity because of spectral broadening seriously degrades the performance of a Raman resonator by reducing the 1121 nm circulating power and the 1178 nm output power. Therefore, it is important to understand the conditions which minimize 1121 nm power leakage, maximize 1121 intracavity and 1178 nm output power while enabling a manageable Stimulated Brillouin Scattering gain for narrow linewidth systems. It was found that cavity lengths longer than approximately 40 m didn't result in significantly more 1121 nm linewidth broadening. Relative to the high reflectivity bandwidth of the fiber Bragg gratings, it was found that 4 nm FBGs seemed to optimize 1178 nm amplification while minimizing the amount of 1121 nm power leakage. A two stage high power 1178 nm Raman system was built and 20 W of 1178 nm output power was achieved with a polarization extinction ratio of 21 and nearly diffraction limited beam quality. Linewidth broadening was found to increase as the 1178 nm output increased and was approximately 8 GHz when the 1178 nm output power was 20 W. Because of the linewidth broadening, a co-pumped second Stokes Raman laser system is not useful for the sodium guidestar laser application which requires narrow linewidth.

15. SUBJECT TERMS

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Investigations of a Dual Seeded 1178 nm Raman Laser System

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ABSTRACT

The leakage of 1121 nm power from a resonator cavity because of spectral broadening seriously degrades the performance of a Raman resonator by reducing the 1121 nm circulating power and the 1178 nm output power. Therefore, it is important to understand the conditions which minimize 1121 nm power leakage, maximize 1121 intracavity and 1178 nm output power while enabling a manageable Stimulated Brillouin Scattering gain for narrow linewidth systems. It was found that cavity lengths longer than approximately 40 m didn't result in significantly more 1121 nm linewidth broadening. Relative to the high reflectivity bandwidth of the fiber Bragg gratings, it was found that 4 nm FBGs seemed to optimize 1178 nm amplification while minimizing the amount of 1121 nm power leakage. A two stage high power 1178 nm Raman system was built and 20 W of 1178 nm output power was achieved with a polarization extinction ratio of 21 and nearly diffraction limited beam quality. Linewidth broadening was found to increase as the 1178 nm output increased and was approximately 8 GHz when the 1178 nm output power was 20 W. Because of the linewidth broadening, a co-pumped second Stokes Raman laser system is not useful for the sodium guidestar laser application which requires narrow linewidth.

Keywords: Raman resonator, linewidth broadening, fiber Bragg grating bandwidth

1. INTRODUCTION

Current narrow linewidth sodium guidestar lasers are either constructed using slab[1-3] or fiber laser technology[4-15]. Slab technology generally involves sum-frequency mixing of 1064 and 1319 nm in a lithium triborate crystal to obtain 589 nm. Another way of achieving the desired output wavelength of 589 nm for sodium guidestar laser applications is through frequency doubling of 1178 nm light. Researchers at the European Southern Observatory (ESO) have been successful in constructing a narrow linewidth sodium guidestar laser based on frequency doubling of the output of a Raman fiber amplifier operating at 1178 nm[4-9]. The ESO reported achievement of 39 W of narrow linewidth 1178 nm or 26.5 W of 589 nm when frequency doubled. More recently, 44 W of 1 MHz linewidth 1178 nm continuous wave light was obtained by Raman amplification of a distributed feedback diode laser in a variably strained polarization-maintaining fiber with a record-high optical efficiency of 52% when pumped with a linearly polarized 1120 nm fiber laser[10,11]. Because of the all-polarization maintaining configuration, a polarization extinction ratio of 30 dB was obtained and a 20 time's reduction in the effective stimulated Brillouin scattering coefficient was achieved. A 24.3 W 589 nm laser was created from this by using an external resonant doubling cavity. Also, 22 W of single-frequency 1178 nm was obtained from a counter-pumped two-stage Raman fiber amplifier using an acoustically tailored fiber[12]. In addition, 24.6 W of single-frequency 1178 nm has been obtained from an ytterbium-doped photonic band gap fiber laser with a 320 kHz linewidth[13]. Finally, 85 W of single frequency (1 MHz) 1178 nm was obtained from a two-stage counterpumped Raman laser system in PM 10/125 fiber with a good beam quality (M2) of 1.1. Thirty steps of variable strain were applied to the high power stage and a 20x reduction in Stimulated Brillouin Scattering was observed. Also, in a pulsed format, 120 W of peak 1178 nm power was obtained for repetition rates from 500 Hz to 10 kHz and pulse durations from 1 ms to 30 μs[14,15].

Recently, a dual 1069 nm pump and 1178 nm signal seeded Raman laser system utilizing a 1121 nm resonator cavity defined by high reflector fiber Bragg gratings (FBGs) has been under investigation[16]. The original idea supposed that buildup of high 1121 nm power levels within a short resonator cavity would enable significant amplification of the 1178 nm while avoiding problems with Stimulated Brillouin Scattering (SBS). As it turned out, buildup of high 1121 nm intracavity power levels has been prevented due to significant 1121 nm power leakage around the FBGs, spectrally. A failure to build significant 1121 nm intracavity power in shorter resonator cavities has driven the need to use longer resonator cavities to enable significant amplification of the 1178 nm. Because the 1178 nm is narrow linewidth, usage of longer resonator cavities has led to issues involving Stimulated Brillouin scattering. To enable the most optimum design within the constraints, the amount of linewidth broadening was previously studied as a function of the cavity length for a fixed FBG bandwidth[17]. In this paper, the amount of linewidth broadening was studied as a function of the FBG bandwidth for a fixed cavity length. Finally, using the optimum FBG bandwidth, a two-stage high power 1178 nm Raman laser system was constructed.

2. OVERVIEW OF THE LOW POWER RAMAN LASER SYSTEM FOR EVALUATION OF 1121 NM INTRACAVITY LINEWIDTH BROADENING

The Raman system discussed in this article is seeded both with the zeroth Stokes pump wavelength at 1069 nm and the desired second Stokes output wavelength at 1178 nm, see Figure 1. In this system, the 1069 nm is first amplified and is then Raman converted to 1121 nm in a cavity defined by high reflector fiber Bragg gratings centered at 1121 nm. The 1178 nm signal is then amplified as it passes through the cavity. The system is entirely comprised of 10/125 polarization maintaining (PM) fiber with germanosilicate fiber being utilized in the Raman resonator. Because of significant amounts of 1121 nm power leakage past the input FBG in an upstream direction, multiple three wavelength wavelength division multiplexers (WDMs) are used to dump the 1121 nm into the cladding. This is necessary since the 1121 nm would compete favorably with the 1069 nm for gain thereby causing the 1069 nm pump power to roll over. In addition, high power levels of 1121 nm propagating upstream could potentially damage the expensive sources. Previous work involving this system is described in reference 16. In order to investigate 1121 nm linewidth broadening in the resonator cavity, two tap couplers were inserted in the cavity, one next to the input and the other next to the output FBG, Figure 1.

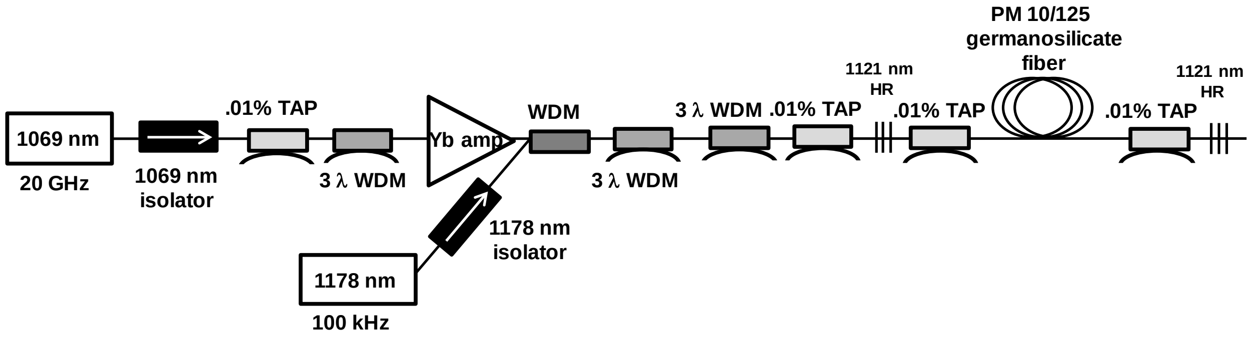

Figure 1. Schematic diagram of a single cavity Raman laser system, pumped with the zeroth Stokes at 1069 nm and seeded with the second Stokes at 1178 nm, that has been configured to enable study of linewidth broadening in the resonator cavity.

In this system, both tap couplers are within 1.5 m or less of their respective FBG and enabled sampling of light traveling in both the forward and backward directions within the Raman cavity. The output power from the forward and backward legs of each tap contained a contribution from each of the wavelengths (1069, 1121, and 1178 nm) which was reflective of the characteristic splitting fraction of the tap coupler as well as the intracavity power traversing in either the forward or backwards directions at each wavelength. In addition, the back tap leg situated upstream from the resonator cavity provided insight into the composition of the light leaking backward past the input FBG or the light being emitted from the laser output, respectively. Although the usage of tap couplers provided great insight into what was happening in the resonator cavity, the downside to this was four additional dissimilar splices of silica to germanosilicate fiber that helped to significantly increase the attenuation of all three wavelengths within the resonator cavity. Previously Randoux[18] employed two similarly placed tap couplers to study the spectral broadening associated with a single pass inside a cavity pumped with 1100 nm that was comprised of 500 m of polarization maintaining fiber defined by non-chirped FBGs centered at approximately 1160 nm.

3. RESULTS OF LINEWIDTH BROADENING STUDIES

3.1. Linewidth Broadening as a Function of the Cavity Length for a Fixed FBG Bandwidth

The degree of 1121 nm linewidth broadening and the corresponding percentage of power leakage was investigated as a function of resonator cavity length for the following cavity lengths: 15, 27, 40, 65, 90, 115, and 140 m. FBGs having a bandwidth of 3 nm were utilized for this study. Relative to system performance, the PERs of both the 1178 output power and the intracavity 1121 nm power were approximately 18-20. From measurements of the output power levels, as expected, greater utilization of 1069 nm, increased output power levels of 1178 nm, and a decreased threshold for resonance were the result as the cavity increased in length, Figure 2. The behavior of the amount of 1121 nm leakage from the output FBG was more complicated. For similar levels of 1069 nm pump power above threshold, the amount of 1121 nm power leakage decreased for cavity lengths longer and shorter than 40 m. This behavior has to do with fact that the amount of linewidth broadening (and amount of 1121 nm power leakage) tends to increase as both the length of the cavity and the 1121 nm intracavity power levels increase. But, because the 1121 nm intracavity power level decreases when the length of a cavity increases for a fixed level of 1069 nm pump power, the amount of 1121 nm power leakage reaches a maximum at a certain length.

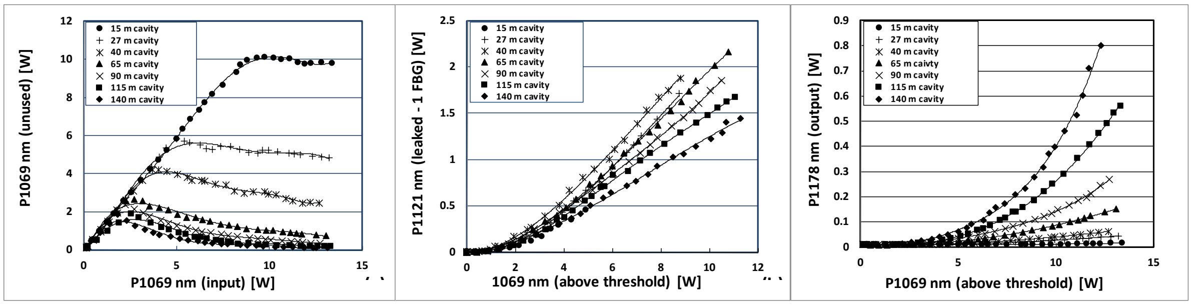

Figure 2. (a) Unused 1069 nm pump power versus the input 1069 nm pump power, (b) 1121 nm power leakage from the output FBG as a function of the level of 1069 nm pump power above threshold, and (c) 1178 nm output power as a function of the 1069 nm pump power above threshold, all (a) to (c) for the following seven cavity lengths: 15, 27, 40, 65, 90, 115, and 140 m defined by 3 nm FBGs.

Insight was obtained into the level of intracavity 1121 nm power propagating in the forward and backwards directions as a function of the level of 1069 nm pump power above threshold through measurement of spectra from 1050 to 1200 nm along with the corresponding power out of the intracavity tap couplers. The composition of the power coming out of the tap couplers was dependent on the intracavity power levels of the different wavelengths as well as the splitting percentages of the tap coupler at the different wavelengths. The composition of the power emerging from a tap coupler could be discerned from the full spectrum (1050 to 1200 nm) since the percentage of power at each wavelength (1069,

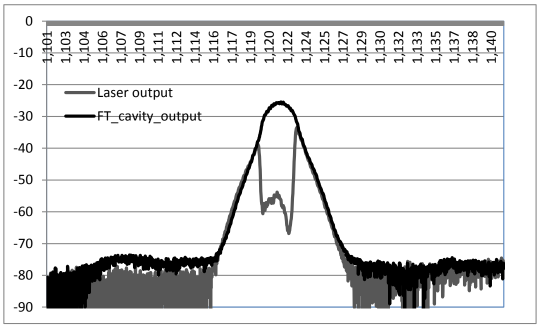

Figure 3. Alignment of a spectrum of the 1121 nm intracavity power impinging on the output 3 nm FBG of the laser resonator from within the resonator cavity with a spectrum of the l121 nm power escaping past the output 3 nm FBG.

1121, and 1178) is related to the percentage contribution of the area of each spectral peak to the total area within the spectrum. From this information, the power out of the tap coupler at each wavelength could be determined and then, from the splitting percentages of the tap coupler, the power in the three wavelengths within the resonator cavity could be determined. The percentage power loss of 1121 nm out of a FBG in this work was determined by aligning the spectrum of light propagating out of either the input FBG (backward direction out of the tap coupler immediately upstream from the resonator cavity) or the output FBG (forward direction from the laser output) with the corresponding spectrum of light impinging on the respective grating from within the cavity (spectrum out of the backward leg of the intracavity tap coupler next to the input FBG or forward leg of the intracavity tap coupler next to the output FBG for the backward and forward directions, respectively). Since the light propagating in the forward and backward directions is of a similar nature, these analyses were carried out for only light propagating in the forward direction. Shown in Figure 3 is an example of a spectrum out of the forward leg of the intracavity tap coupler next to the output FBG aligned with the spectrum from the output FBG of the laser.

Upon determination of the 1121 nm intracavity power level circulating in the forward direction (note that the 1121 nm power circulating in the reverse direction is similar), it is apparent that the relationship of the 1121 nm forward circulating power to the 1069 nm pump power above threshold is sublinear, Figure 4a. Also, of note is that 1121 nm power grows at a faster rate for the same 1069 nm pump level above threshold for the shorter cavities when there is less 1121 nm linewidth broadening. This is probably due to the fact that there is less power lost at the FBGs. Upon determination of the percentage of the broadened 1121 nm power which has leaked spectrally past the output FBG along with the intracavity 1121 nm power propagating in the forward direction for increasing levels of 1069 nm pump power, one can see that there appears to be a linear or nearly-linear relationship between the percentage of 1121 nm power leakage past the output FBG and the intracavity 1121 nm power propagating in the forward direction, Figure 4b.

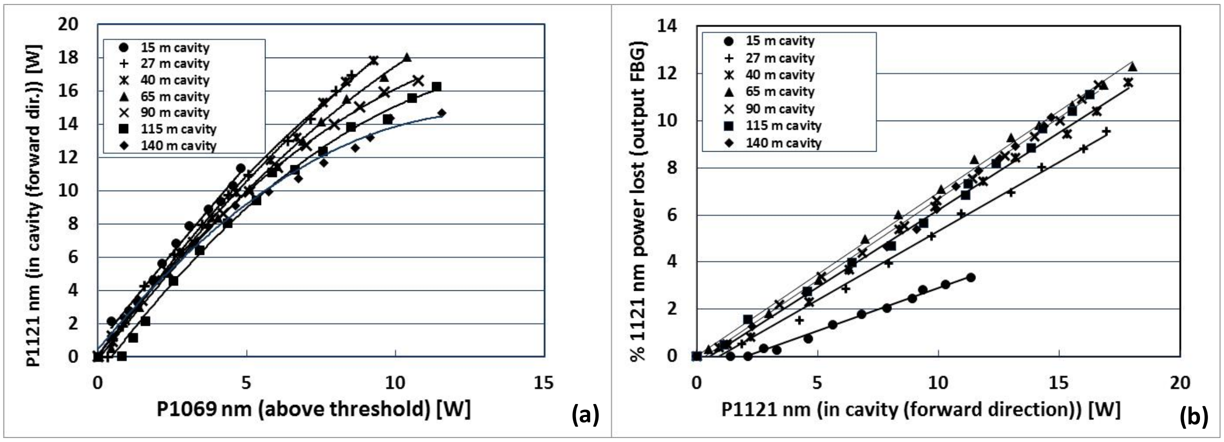

Figure 4. (a) 1121 nm power circulating in the forward direction in the resonator cavity as a function of the 1069 nm pump power above threshold; (b) Percentage of spectrally broadened 1121 nm power leakage past the output FBG versus 1121 nm intracavity power propagating in the forward direction both for the following cavity lengths: 15, 27, 40, 65, 90, 115, and 140 m. The cavities were comprised of polarization maintaining 10/125 germanosilicate fiber and defined by 3 nm FBGs.

For resonator cavity lengths longer than 40 m, differences in the percentage of 1121 nm power spectrally leaking past the output FBG as a function of the 1121 nm intracavity power propagating in the forward direction are not real discernible. It is obvious for cavity lengths 40 m and shorter that the percentage of 1121 nm power spectrally leaking past the output FBG decreases significantly for a given 1121 nm intracavity power level. It should be noted that once steady state has been achieved in a resonator cavity, one pass down a cavity is representative of the evolution of the spectral shape of the intracavity power since the spectral shape is reset after each reflection from a FBG. With this in mind, the experimental data lends some support to the supposition that the spectral shape of the 1121 nm power initially spreads significantly as it traverses the first 40 m of a cavity for a given 1121 nm intracavity power, with the rate of spread possibly diminishing for lengths longer than 40 m. For all cavity lengths investigated, the relationship between the percentage of 1121 nm power spectrally leaking past the output FBG and the 1121 nm power in the cavity (in the forward direction) appeared to be nearly linear within experimental error. Vatnik[19] also found a nearly linear relationship between the full width at half maximum (FWHM) of the generation (Stokes) spectrum and the Stokes power for an approximate 12 m cavity pumped with 12 W of 1115 nm power. Vatnik's cavity was comprised of 980-HP fiber and 98% reflective FBGs having half-maxima of 0.3 nm tuned to 1173 nm.

3.2. Linewidth Broadening as a Function of the FBG Bandwidth for a Fixed Cavity Length

The degree of linewidth broadening was investigated for an approximate 85 m cavity for FBG pairs having bandwidths of 1, 2, 3, 4, and 5 nm. Relative to system performance, the polarization extinction ratios (PERs) for the 1178 nm output power and the 1121 nm intracavity power were approximately 18-22. Generally, the 1121 nm power built to higher levels, for larger FBG bandwidths, Figure 5a, than for the smaller FBG bandwidths. Also, as expected, the percentage of 1121 nm intracavity power leaking around both the input and output FBGs, Figure 5b, was decreased for larger FBG bandwidths.

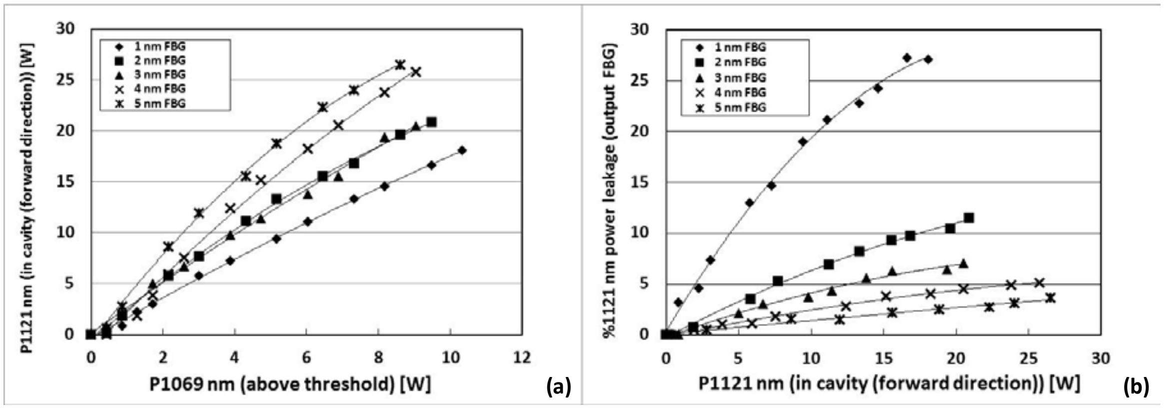

Figure 5. (a) 1121 nm circulating power in the forward direction as a function of the level of pump power above threshold and (b) Percentage of 1121 nm power leakage around the output (FBG) (the power leaking around the input FBG upstream is similar) as a function of the 1121 nm intracavity power level in the forward direction (note that the intracavity 1121 nm power circulating in the reverse direction is similar) both for fiber Bragg grating bandwidths of 1-5 nm.

Another important measure of the effectiveness of FBGs of a certain bandwidth is how well the 1178 nm input seed is Raman amplified. Interestingly, as can be seen in Figure 6a-c, the 1178 nm is amplified the best in Raman cavities defined by 4 nm high reflector FBGs. This may have to do with a decrease in the Raman gain curve at the lower and upper ends of the spectrum of wavelengths centered at 1121 nm within the resonator cavity defined by 5 nm high reflectivity FBGs. Note that this spectrum extends beyond the lower and upper ends of the high reflectivity bandwidth of the FBG. As a result, the Raman resonator cavity defined by 4 nm high reflectivity FBGs appears to be optimum in that it results in a maximum amplification of 1178 nm. Although, more power builds in the resonator cavity defined by 5 nm FBGs, because a significant portion of this power spectrally lies in regions where the Raman gain is not a maximum, the 1178 nm, as a result, is not as well amplified.

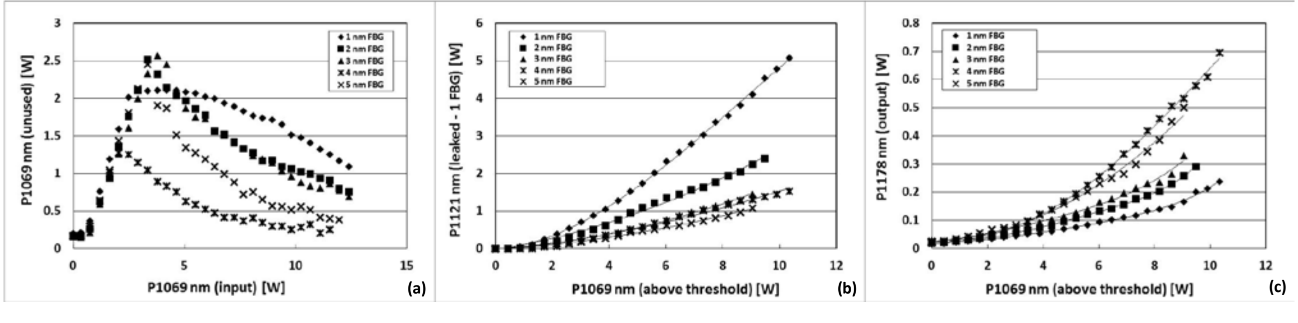

Figure 6. (a) Unused 1069 nm pump power versus the input 1069 nm pump power, (b) 1121 nm power leakage from the output FBG as a function of the level of 1069 nm pump power above threshold, and (c) 1178 nm output power as a function of the 1069 nm pump power above threshold, all (a) to (c) for the following five fiber Bragg grating bandwidths: 1, 2, 3, 4, and 5 nm and an 85 m resonator cavity.

For the cavity studied, the linewidth of the 1178 nm output power was measured with a 10 GHz Fabry Perot interferometer and was found to be dependent on the output power level of 1178 nm. Generally, the linewidth of the 1178 nm output power increased minimally from 1 to 2 MHz as the output power level increased to approximately 1 W.

4. OVERVIEW OF THE TWO STAGE HIGH POWER 1178 NM RAMAN LASER SYSTEM

Once the cavity length necessary to effect good amplification of the 1178 nm was determined as well as the optimum fiber Bragg grating bandwidth, a two stage 1178 nm Raman laser system was built. The lower and higher power stages were constructed out of polarization maintaining 10/125 and 20/400 fiber, respectively, see Figure 7.

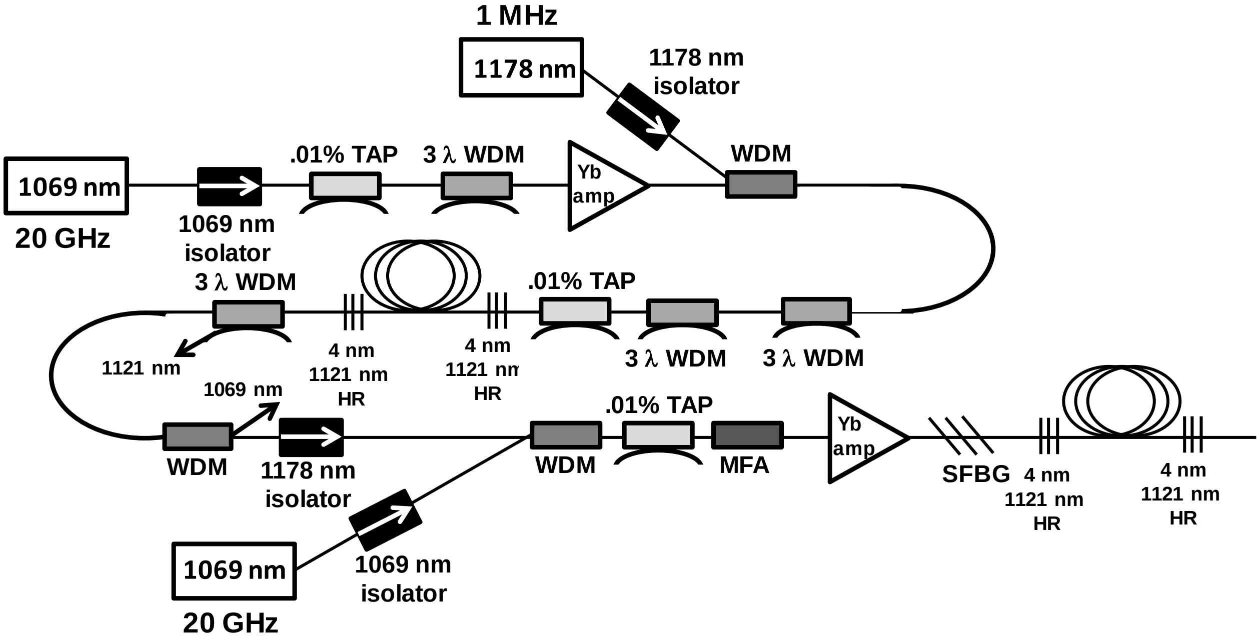

Figure 7. Two stage 1178 nm Raman laser system.

The lower power stage in polarization maintaining 10/125 fiber is similar to that described above with the only differences being the absence of the TAP couplers from the resonator cavity as well as a higher 1178 nm seed level of 800 mW. In addition, the resonator was 85 m in length, was comprised of two temperature zones of roughly 25°C and 50°C, and was defined by 4 nm FBGs. Before the lower power stage could be used to seed the high power stage in polarization maintaining 20/400 fiber, any residual 1069 and 1121 nm had to be first removed from the output of the low power stage. This was accomplished by usage of first, a three wavelength WDM to remove the 1121 nm followed by a two wavelength WDM to strip away the 1069 nm. After passage of the light through both components, only negligible amounts of 1121 nm remained with approximately 99% of the total power being comprised of 1178 nm and 1% being comprised of 1069 nm. This power was then inserted into an 1178 nm isolator and into the core of a fiber via a WDM along with approximately 800 mW of 20 GHz 1069 nm. After the WDM was a TAP coupler to enable monitoring of the light traversing upstream to include any 1121 nm along with the 1178 nm back reflection. Following the TAP coupler, the mode area of the fiber was expanded from 10/125 to 20/400 via a mode field adapter. Upon entry of the light into an ytterbium fiber amplifier comprised of 5.5 m of PM 20/400 gain fiber, the 1069 nm was preferentially amplified by a great extent. Output 1069 nm power levels up to 100 W were obtainable using wavelength stabilized LIMO 976 nm pumps. Both wavelengths then passed through a slated fiber Bragg grating, whose purpose was to remove 1121 nm traversing upstream in the PM 20/400 fiber, and then into a 100 m resonator cavity defined by 4 nm high reflector fiber Bragg gratings. As described before, the 1069 nm was then Raman converted to 1121 nm which then, amplified the 1178 nm upon passage through the cavity. The length of the resonator cavity in the high power stage was 100 m with one spool cooled to approximately 16°C with the other at approximately 25°C.

5. RESULTS OF A TWO STAGE HIGH POWER 1178 NM RAMAN LASER SYSTEM

The low power stage which was seeded with 800 mW of both 1069 and 1178 nm, respectively, was fully characterized. Almost 3 W of 1178 nm output power was obtainable from the low power stage along with about 1 W of residual 1069 and about 1 W of 1121 nm which had spectrally leaked past the output high reflector FBG, Figure 8a. The polarization extinction ratio of the 1178 nm was 23.8. In addition, there was a slight broadening of the linewidth across the range of 1178 nm output powers from roughly 4 to 5 MHz as the 1178 nm output power increased from .35 to 3 W, Figure 8b. In addition, because the linewidth doesn’t broaden substantially, two temperature zones were used to mitigate SBS which is evident through the back reflection shown in Figure 8c. Throughout the range of 1178 nm output power levels, SBS was not a problem. Finally, because it was found that the 1178 nm isolator between the stages could not tolerate input power levels of 1178 nm at the 2 W level, the low power stage was operated at an 1178 nm output power level of 1.65 W which resulted in approximately 1 W 1178 nm power passing through the isolator.

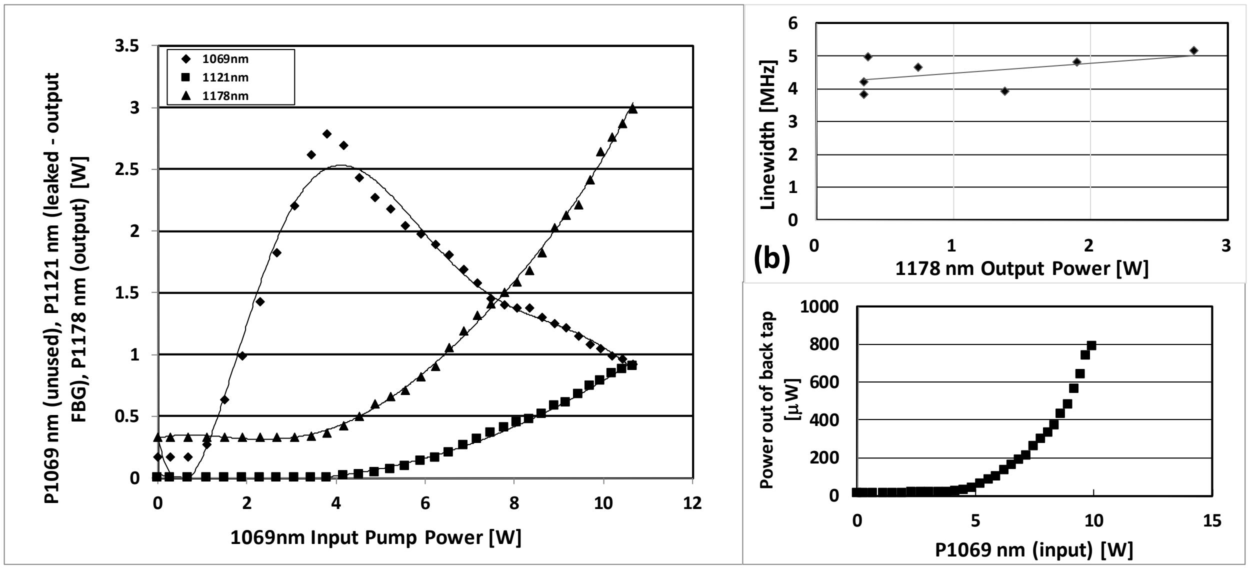

Figure 8. (a) 1069 nm unused power, 1121 nm power leaked around the output FBG, and 1178 nm output power as a function of the 1069 nm input pump power, (b) Linewidth of the 1178 nm output as a function of the 1178 nm output power and (c) Power out of high power back tap (immediately upstream from the high power resonator cavity) as a function of the 1069 nm input pump power for the low power stage.

The high power stage was seeded with 900 mW of 1069 nm and as mentioned above, 1.65 W of 1178 nm. Following amplification of the light in the ytterbium amplifier, approximately 600 mW of 1178 nm and up to 85 W of 1069 nm pump power entered the cavity. The cavity was comprised of two spools, 50 m each, of PM 20/400 germanosilicate Raman fiber held at 20 and 25°C, respectively. Upon ramp up of the 1069 nm input pump power, it is observed that threshold occurred in the neighborhood of 15 W of 1069 nm pump power. As the 1069 nm pump power increased above threshold, both the leaked 1121 nm intracavity power and 1178 nm output power increased at first faster than linearly to approximately 50 W of input pump power followed by a sublinear increase for pump powers above 50 W, Figure 9a. This is more than likely a temperature related effect associated with the pump diodes. The results shown here were produced with up to 85 W of input 1069 nm to avoid a catastrophic event that could damage the system. As can be seen in Figure 9a, the output of the system at a 1069 nm pump power level of 85.9 W was comprised of 1.2 W of residual 1069 nm, 4.2 W of spectrally leaked 1121 nm, and 19.5 W of 1178 nm. Of great importance is the linewidth, polarization extinction ratio, and the beam quality of the output 1178 nm power since some applications require a narrow linewidth polarized beam. The PER of the 1178 nm was measured with a polarizing beam splitting cube to be 21. The linewidth of the output was measured with a 30 GHz Thorlabs Fabry-Perot interferometer. It was found that the linewidth seemed to increase sub-linearly as the 1178 nm output power increased, Figure 9b. As can

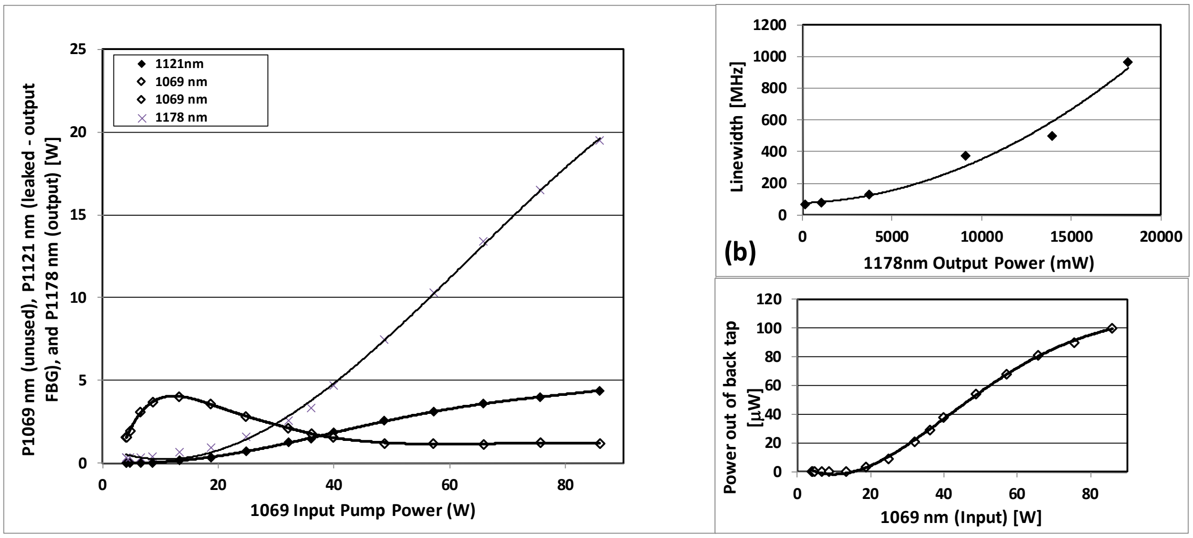

Figure 9. (a) 1069 nm unused power, 1121 nm power leaked around the output FBG, and 1178 nm output power as a function of the 1069 nm input pump power, (b) Linewidth of the 1178 nm output as a function of the 1178 nm output power and (c) Power out of high power back tap (immediately upstream from the high power resonator cavity) as a function of the 1069 nm input pump power for the high power stage.

be seen, the linewidth at the maximum output power of approximately 20 W was roughly 8 GHz. Linewidth broadening of the output from a co-pumped first Stokes Raman laser system was previously seen by Dajani[20]. Because of linewidth broadening, this particular system design is not real useful for sodium guidestar laser applications. The back reflection, Figure 9c, was actually significantly less over the range of input pump powers relative to that in Figure 8c. This is indicative of the SBS being less of a problem in the high power stage. The increase in the 1178 nm linewidth associated with the 1178 nm output of the high power stage suppressed the SBS since there was virtually no back reflection originating from SBS seen in the spectrum, Figure 10b. This is quite different from what was observed from the low power stage where the linewidth broadening was minimal, Figure 10a.

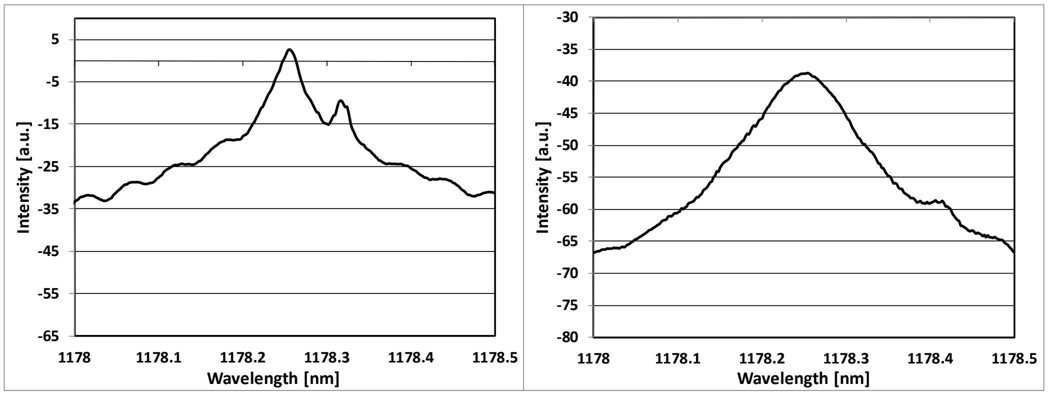

Figure 10. (a) Intensity of back reflection versus wavelength for the low power stage and (b) Intensity of back reflection versus wavelength for the high power stage.

Finally, the beam quality of the 1178 nm output was measured with a Thorlabs M2 machine model M2MS-BP209IR and was found to be 1.15 in the x direction and 1.14 in the y directions, see Figure 11a. The two dimensional profile of the output beam also had the appearance of being single mode, Figure 11b, even though the core diameter of the output was 25 μm. This is promising for applications requiring propagation over long distances.

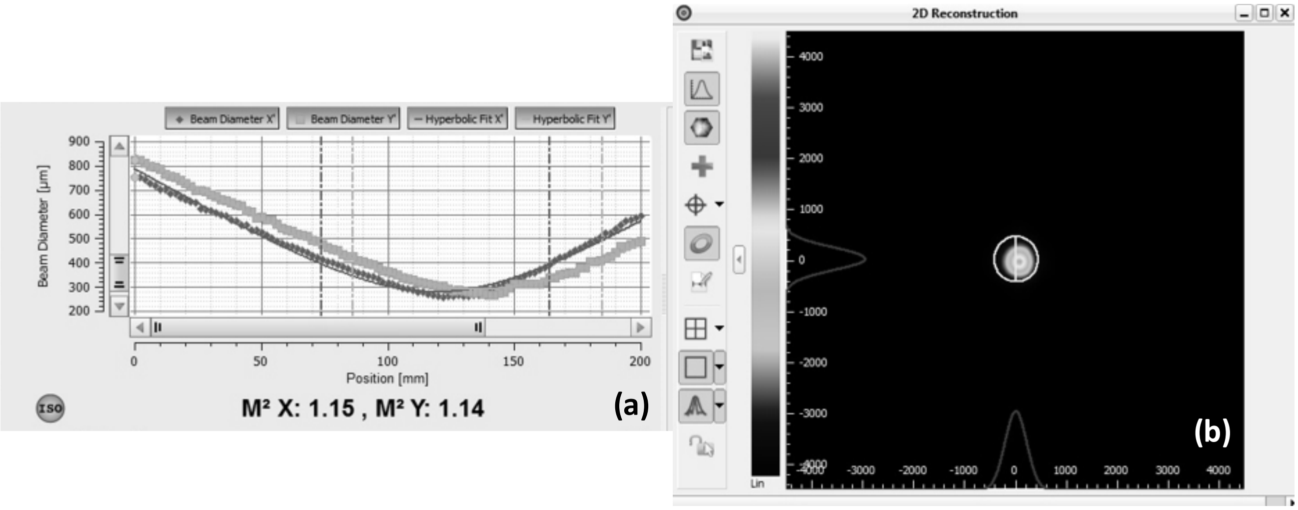

Figure 11. (a) 1178 nm beam diameter as a function of position, and (b) two dimensional profile of the 1178 output beam.

5. CONCLUSION

The leakage of 1121 nm power because of spectral broadening from a resonator cavity seriously degrades the performance of a Raman resonator by reducing the 1121 nm circulating power and the 1178 nm output power. Therefore, it is important to understand the conditions which minimize 1121 nm power leakage, maximize 1121 intracavity and 1178 nm output power while enabling a manageable SBS gain for narrow linewidth systems. It was found that cavity lengths longer than approximately 40 m didn't result in significantly more 1121 nm linewidth broadening. Therefore, usage of a longer resonator cavity length doesn't impact this greatly and is desirable in order to obtain good conversion of 1069 to 1121 nm. On a down note, if 1178 nm were to stay narrow linewidth, SBS would be an issue. A mitigation technique such as multiple temperature zones or multiple zones of strain would be necessary to mitigate SBS. Relative to the high reflectivity bandwidth of the fiber Bragg gratings, it was found that 4 nm FBGs seemed to optimize 1178 nm amplification while minimizing the amount of 1121 nm power leakage. Maximum amplification of the 1178 nm probably occurred for the 4 nm FBGs because the amount of intracavity 1121 nm spectral power that fell within the region of maximum Raman gain was maximized. A two stage high power 1178 nm Raman system was built and 20 W of 1178 nm output power was achieved with a PER of 21 and nearly diffraction limited beam quality. Linewidth broadening was found to increase as the 1178 nm output increased and was approximately 8 GHz when the 1178 nm output power was 20 W. Because of the linewidth broadening, a co-pumped second Stokes Raman laser system is not useful for the sodium guidestar laser application which requires narrow linewidth.

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