Blue Pr^{3+}-Doped ZBLAN Fiber Upconversion Laser

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Abstract

We demonstrate for the first time blue laser emission from a direct semiconductor laser diode pumped Pr^{3+}-doped upconversion fiber laser. This laser produced over 1 mW of power at a wavelength of 492 nm using pump lasers operating at 830 and 1020 nm.

Introduction:

The upconversion fiber laser (UFL) is a potentially compact solution for visible CW radiation. The trivalent praseodymium ion suspended in a ZBLAN fluoride glass host offers a variety of transitions with fluorescence in the red, green and blue wavelengths as shown in Fig. 1. The visible upconversion process consists of two steps requiring two pump sources operating at wavelengths near 1017 nm and 831 nm respectively. The first step involves ground-state absorption, (GSA), of 1017 nm pump photons from the $^3H_4$ level to the $^1G_4$ level (110 μs lifetime). An excited-state absorption of 831 nm pump light places the ion in the ^3P_o metastable state which has a lifetime of approximately 47 μs [1]. With sufficient pump power, the upper state (^3P_o) becomes inverted with respect to the ground-state ($^3H_4$) creating optical gain. Visible laser emission has been demonstrated at a variety of wavelengths from red to blue [2-5]. Most experiments to date have concentrated on large and expensive Ti-sapphire lasers [2,5], or Ti-sapphire laser pumped Yb^{3+} -doped silica fiber lasers as pump sources [6]. A practical compact blue UFL requires direct pumping with semiconductor diode lasers. There are a number obstacles to direct semiconductor laser pumping including: (1) the limited output power of semiconductor pump sources, particularly at a wavelength of 1017 nm, (2) coupling the spatially non-gaussian light from the semiconductor pump lasers to the small core of the active ZBLAN fluoride fiber, (3) creating stable high reflectance blue mirrors at the ends of the fiber cavity and (4) designing the cavity length to obtain laser action on the low-gain three-level blue transition [1], while suppressing laser action on the strong 4-level transitions. In this letter, we demonstrate for the first time, to our knowledge, semiconductor laser-pumped operation of a blue Pr-doped ZBLAN UFL.

Experiment:

The UFL has a double end-pumped cavity design as shown in Fig. 2. The 48 cm long ZBLAN fluoride fiber (Galileo Corp.) was doped with 1000 ppm Pr^{3+}. The ZBLAN fiber core diameter and numerical aperture were specified to be 1.7 μm and 0.39 respectively. The pump light was provided by two standard (non-tapered gain section) semiconductor lasers. These pumps provided facet powers up to 200 mW (i_{p1}=224 mA) and 100 mW (i_{p2}=132 mA) at wavelengths of 831 nm and 1017 nm respectively. Cylindrical lenses (Blue Sky Research) were attached to the semiconductor laser submounts to circularize the elliptical beam emitted at the facets. This provided more efficient imaging onto the circular ZBLAN fiber core. The laser cavity was formed by evaporating directly on each end-face of the ZBLAN fiber a 16 layer dielectric stack composed of TiO_2 and SiO_2. Reflectances of 99.4 % and 93 % were obtained at a wavelength of 490 nm based on transmission measurements performed on an evaporator witness slide. The mirror loss for the high gain $^3P_0$-$^3F_2$ red transition was approximately 99%, which was sufficient to suppress lasing. The blue laser light was separated from the incident pump light through an angled dichroic mirror as shown in the figure. Some of the 831 nm pump light was recycled with a 35 % reflector provided by the end-face mirror, while no recycling of the 1017 nm pump light was performed. The output spectrums of both pump lasers were significantly altered by interaction with the wavelength and power dependent feedback from the UFL cavity. This interaction caused the 1017 pump spectrum to split into 6 lines with a nominal spacing of 1.5 nm.

Laser Characteristics:

The blue output spectrum for pump currents of i_{p1}=123 mA, i_{p2}=131 mA, was comprised of several lines centered about 492 nm as shown in Fig. 3. At output powers below 100 μW, only a single laser line was observed within the 0.2 nm optical spectrum analyzer resolution bandwidth. The Pr^{3+} four-level transitions corresponding to green, orange and red (both 635 nm and 718 nm) were below their respective lasing thresholds. This laser appears to be free of warm-up effects that can occur in thulium or erbium-doped visible ZBLAN UFLs. The blue output power was dependent on cavity birefringence which could be varied by rotating a loop in the 48 cm long fiber cavity. The output power, corrected for the blue bandpass filter transmission loss (T=63%), is shown in Fig. 4 as a function of the 1017 nm pump current for various 831 nm pump injection current levels. An inflection in the slope of the characteristic occurs as the 831 nm pump current is increased. At low 831 nm pump currents, some saturation with 1017 pump currents is observed. At higher 831 nm pump currents (~ 70 mA) the blue output is linear with 1017 nm pump current, but saturates with increased 831 nm pump power. This indicates that the laser output is being limited by ground-state pump absorption. Therefore an increase in 1017 nm pump power will lead to an increase in the blue output power until a point is reached where saturation again occurs requiring increased 831 nm pump power. This is consistent with the weak GSA of the Pr^{3+} ion [1]. From Fig. 4, the required total (831 nm and 1017 nm) threshold current for lasing was ~130 mA which is the lowest reported value for a blue upconversion laser. The electrical to optical power conversion efficiency for this laser was approximately 0.25% at an output power of 1 mW.

The Pr^{3+}-UFL relative intensity noise, RIN, was measured with a silicon photoreceiver and electrical spectrum analyzer. The RIN spectrum is shown in Fig. 5 indicating a relaxation resonance peak at a frequency of 286 KHz. The peak RIN of -82 dB/Hz sometimes increased to -65 dB/Hz during the experiment. It could be reduced again with a change in pump laser current. These RIN changes are probably due to changes in the laser field spectrum due to environmental effects on the fiber laser cavity. Beyond 800 KHz, the RIN falls below the thermal noise (-105 dB/Hz) of the detection system. The Fabry-Perot cavity peaks are situated at much higher frequencies $f = c/2nL \sim$ 200 MHz, and hence are not observed here.

Conclusions:

We have demonstrated, for the first time to our knowledge, semiconductor diode-pumped upconversion lasing at a wavelength of 492 nm in Pr^{3+}-doped ZBLAN fluoride fiber. Output powers in excess of 1 mW were obtained when pumped at wavelengths of 1017 nm and 831 nm simultaneously. A low total threshold current of 130 mA for the combined 831 nm and 1017 nm pump lasers was obtained. The electrical to optical power conversion efficiency, and the maximum slope efficiency with respect to combined pump laser facet powers, were 0.25% and 0.6% respectively.

References

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Figure Captions

Fig. 1 Energy level diagram for Pr^{3+} doped ZBLAN fluoride glass showing relevant pump and lasing transitions.

Fig. 2 Upconversion fiber laser cavity design with two semiconductor laser pumps operating at wavelengths of 831 nm and 1017 nm. CL: attached cylindrical lens, DM: dichroic mirror.

Fig. 3 Oscillation spectrum of 492 nm laser.

Fig. 4 Upconversion output at a wavelength of 492 nm against applied current to the 1017 nm pump with 831 nm pump injection current as a parameter.

Fig. 5 Relative intensity noise spectrum of the Pr^{3+}-doped ZBLAN fluoride fiber laser exhibiting a relaxation resonance peak at 286 KHz.

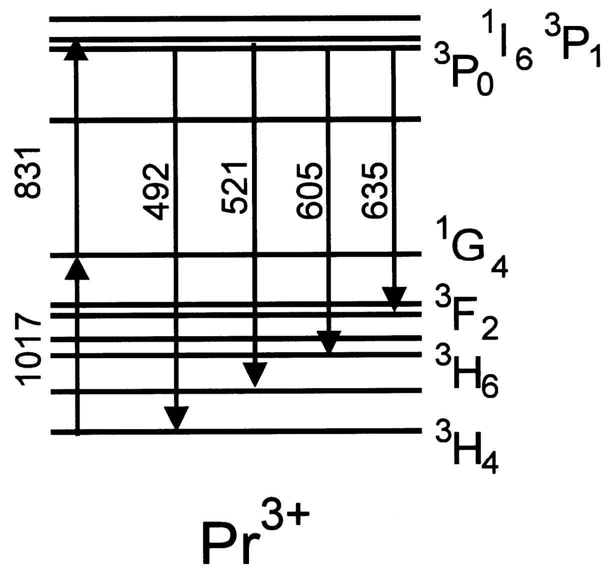

Figure 1

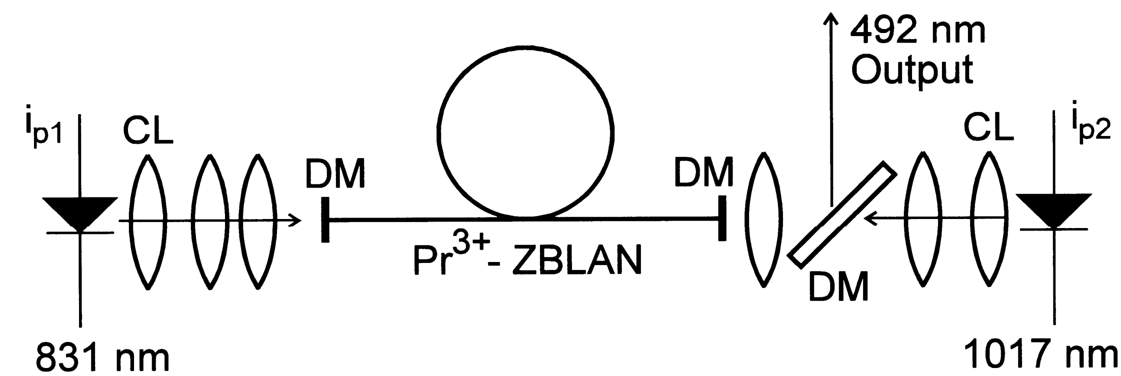

Figure 2

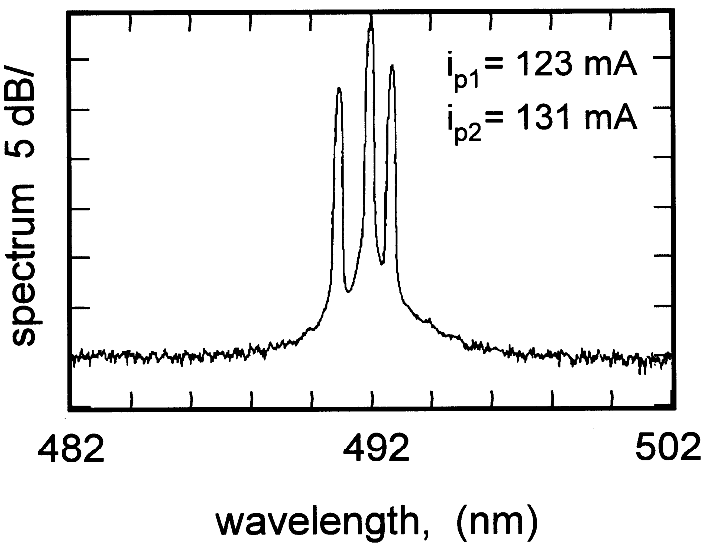

Figure 3

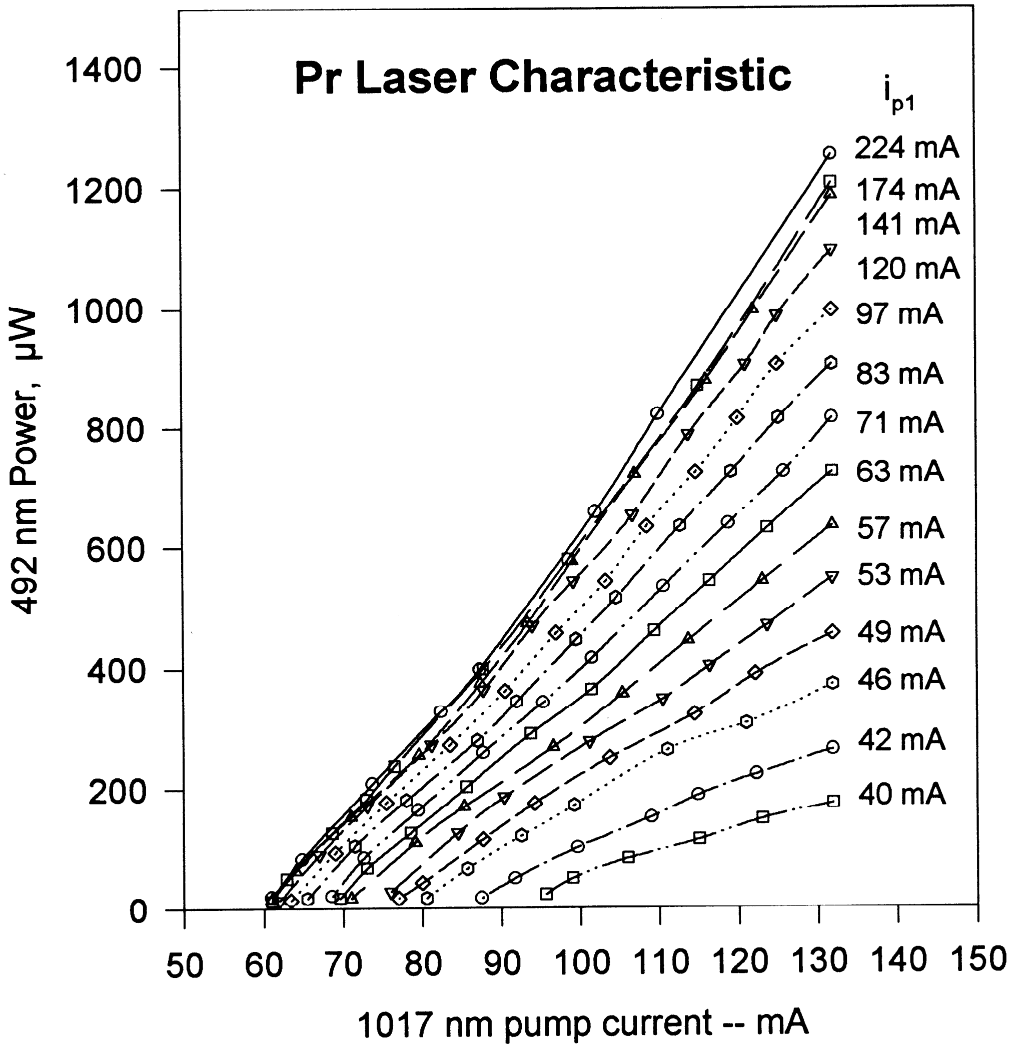
Pr Laser Characteristic
i_p1
224 mA
174 mA
141 mA
120 mA
97 mA
83 mA
71 mA
63 mA
57 mA
53 mA
49 mA
46 mA
42 mA
40 mA
492 nm Power, μW
1017 nm pump current -- mA
0
200
400
600
800
1000
1200
1400
50
60
70
80
90
100
110
120
130
140
150

Figure 4

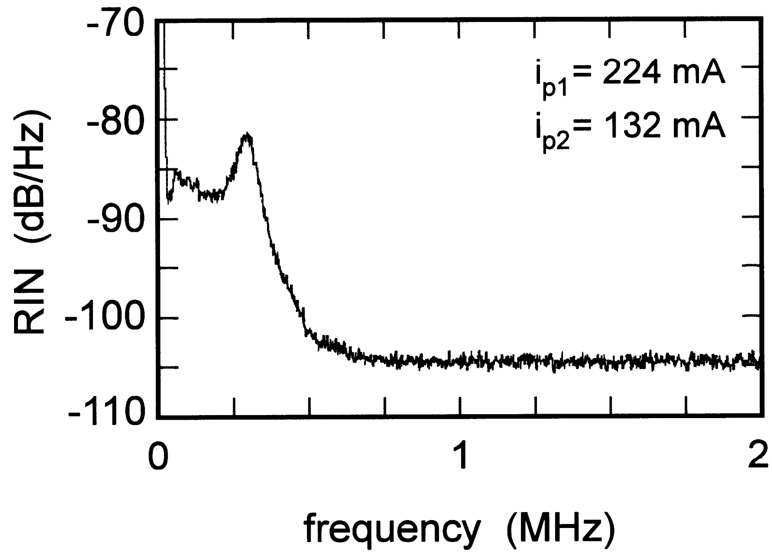
-70
-80
-90
-100
-110
0
1
2
i_{p1}= 224 mA
i_{p2}= 132 mA
RIN (dB/Hz)
frequency (MHz)

Figure 5