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Singly Resonant, Continuous Wave, Sum Frequency Mixing of Two Nd³⁺ Lasers in Periodically Poled Lithium Niobate

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Abstract—We present a method of generating coherent radiation in the orange to red spectral region from a singly resonant sum frequency mixer. The mixer consists of a temperature tuned 6 mm periodically poled lithium niobate nonlinear crystal inside a high finesse 1080 nm Nd : YAP laser. The nonlinear crystal is seeded by a 1444 nm Nd : YAG laser to generate radiation at 618 nm. At 670 mW seeding power of 1444 nm radiation, up to 186 mW of continuous wave radiation at 618 nm were generated, equal to 28% conversion. A beam quality of $M^2 = 1.1$ of the 618 nm radiation and a temperature tuning bandwidth of 7.7 K were measured. Momentarily, the output power of this mixer is limited by beam degradation of the 1080 nm Nd : YAP laser at high pump powers, probably induced by absorption and photo refractive effects in lithium niobate. In a second approach, the intracavity laser and the seeding laser were exchanged. At 2.8 W seeding power of 1080 nm radiation, 380 mW of coherent radiation at 618 nm were generated, equal to 13% conversion. A beam quality of $M^2 < 1.8$ and a temperature tuning bandwidth of $\Delta T = 8.4$ K for the 618 nm radiation were measured. Unfortunately due to high nonlinear intracavity losses, relaxation oscillations of the 1444 nm Nd : YAG laser around 50 kHz were observed above a power of 1.3 W of seeding radiation at 1080 nm, generating up to 100% modulated red output.

Recently, several authors reported on new techniques of generating coherent radiation in the orange–red spectral region around 600 nm by frequency conversion [1–6]. Those wavelengths are of special interest for medical applications (photodynamic therapy) and display technology. Very recently, 2.5 W of nearly diffraction limited radiation at 629 nm where presented by implementing periodically poled lithium niobate (PPLN), showing the possibility to obtain powers above 1 W [7]. Unfortunately, long term stability problems were observed and relatively small spectral bandwidths for fundamental pump lasers were required (<0.01 nm).

In our approach to create red coherent radiation, two longitudinally diode pumped lasers, a Nd : YAG laser at 1444 nm and a Nd : YAP laser at 1080 nm are sum frequency mixed inside a PPLN crystal, which is positioned inside one of the lasers. The setup of our first approach, a singly resonant (at 1080 nm) sum frequency mixer ($SR_{1080 \, nm} - SF$ mixer) is shown in Fig. 1a. The 1080 nm laser was pumped by a fiber coupled diode module (SDL, 792 nm, $\varnothing$400 μm, NA = 0.4) and produced at 9 W pumping power, using a 3% output coupler, 2.2 W of fundamental output power at 1080 nm without, and 1.35 W with the PPLN crystal

inside the resonator. Substituting the output coupler with a highly reflective mirror ($R \sim 99.98\%$), output powers of 16 mW with intracavity beam aperture ($M^2 = 1.1$) or 33 mW without aperture (high transversal modes) were measured. They indicate intracavity powers of roughly 80 W at TEM_{00} mode or 165 W at multi-transversal mode operation. These powers are small compared to what was expected. We assumed this might be a result of intensity dependent loss or distortion mechanisms in PPLN already observed in other experiments [7–9]. The three mirror resonator of the 1080 nm Nd : YAP laser generated a 60 μm beam waist at the position of the nonlinear crystal. Its spectral bandwidth was measured as $\Delta\lambda_{FWHM} = 0.35$ nm. A birefringent filter was implemented in the laser to avoid switching of laser wavelength induced by additional nonlinear losses since Nd : YAP lasers can operate at several different wavelengths around 1080 nm outside of the PPLN phasematching bandwidth [10]. Up to 140 mW of unwanted green radiation at 540 nm were generated inside the unphasematched PPLN crystal in this setup.

The 1444 nm Nd : YAG laser consisted of a 65 mm plan parallel resonator and was also pumped by a fiber coupled diode module (SDL, 808 nm, $\varnothing$400 μm, NA = 0.4). The 7 mm laser crystal required a special laser coating for operation at 1444 nm [11]. The end coating was highly reflective for 1444 nm and additionally

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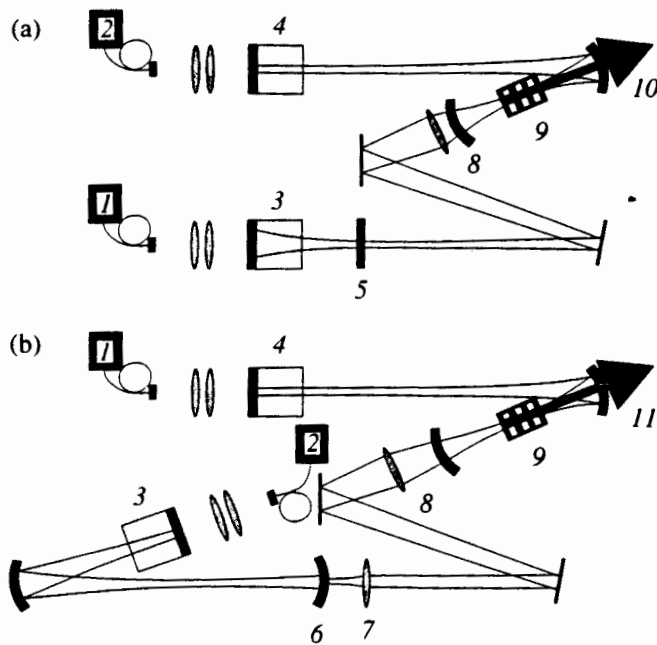[1] Present address: FB Physik, Universität Kaiserslautern, Kaiserslautern, Germany

(a)

(b)

Fig. 1. Singly resonant sum frequency mixer: $SR_{1444\,nm}$ SF mixer (a) and $SR_{1080\,nm}$ SF mixer (b); (*1*) SDL 3450, 10 W diode module @ 808 nm; (*2*) SDL 3450, 10 W diode module @ 797 nm; (*3*) 7 mm Nd : YAG crystal; (*4*) 7 mm Nd : YAP crystal; (*5*) 1.8% output coupler, 550 mW @ 1444 nm; (*6*) 2% output coupler, 2.9 W @ 1080 nm; (*7*) colimating lens; (*8*) focusing lens; (*9*) 6 mm PPLN crystal, 10.5 μm period; (*10*) P_{out} (618 nm) @ 190 mW; (*11*) P_{out} (618 nm) @ 380 mW.

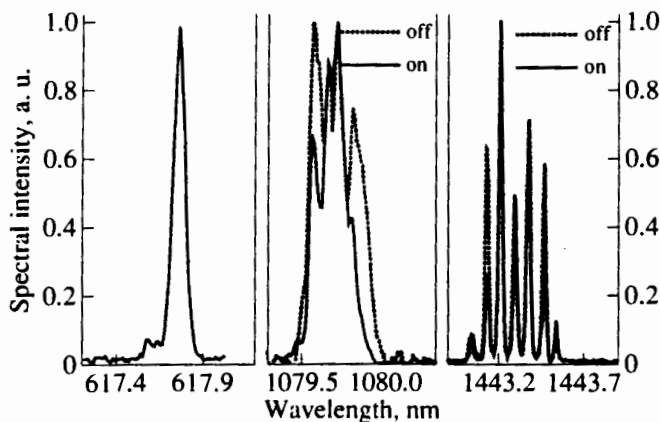**Fig. 2.** Spectrum of the $SR_{1080\,nm}$ SF mixer and its fundamental lasers with mixer on and off; spectral resolution $\Delta\lambda < 0.02$ nm.

highly transmissive at 1360–1320 nm and 1064 nm ($T_{1360\,nm} > 50\%$; $T_{1064} > 95\%$) and the other coating was highly transmissive at 1444 and 1064 nm. The laser was polarized by introducing a 150 μm thick glass plate at Brewster's angle inside the resonator. From this setup up to 670 mW at 1444 nm with an $M^2 = 1.1$ and a spec-

tral bandwidth of $\Delta\lambda_{FWHM} = 0.35$ nm were generated. With a lens, the radiation from this laser was focussed through the endmirror of the 1080 nm Nd : YAP laser into the PPLN crystal.

The PPLN crystal had a length of 6 mm and an aperture of 0.5 mm × 3 mm. Its grating period was 10.5 μm. The theoretical spectral and temperature acceptance bandwidths of this crystal are 0.67 nm and 5.0 K; therefore, no major limitations to efficient sum frequency mixing should apply. The crystal was mounted in an oven and was held at a stabilized temperature of 136°C to achieve phasematching and to avoid photo refractive effects. The end surfaces of the PPLN were antireflection coated for 1080 and 1444 nm.

Several focus diameters for the seed laser were investigated. Even though a theoretical model on singly resonant sum frequency mixing has been proposed [12] it is not explicit on optimized beam waists. However, it was observed that focussing to a beam waist roughly matching the optimum condition for second harmonic generation predicted by [13] resulted in highest output powers. With a beam waist of 30 μm, coherent radiation of 186 mW at 618 nm with an $M^2 = 1.1$ and a spectral bandwidth of 0.08 nm was measured. Its spectrum is shown in Fig. 2. The conversion efficiency from 1444 nm radiation to 618 nm radiation is 28%. By replacing the $R = 100$ mm folding mirror of the Nd : YAP resonator with a $R = 50$ mm mirror, the 1080 nm radiation beam waist inside the PPLN was reduced to 34 μm. Even though this should have increased the output power according to [13], it was decreased. The intracavity intensities of the 1080 nm YAP laser with this setup were even smaller than before and resonator stability was reduced. This is a further indication for the loss mechanisms inside PPLN mentioned above. All results from focus variation are shown in the table.

The temperature dependence of the mixing process was measured. A tuning bandwidth of 7.7 K was observed. This is slightly larger than the theoretically calculated value for mixing single frequency radiation (5.0 K). It might originate from the multi mode structure of the fundamental lasers and could also be an indication for imperfect poling [14]. The noise was measured over a time scale of several tens of seconds. The rms noise of the generated sum frequency output power is smaller 1% (Fig. 3).

In a second approach (Fig. 1b), the two lasers were switched. A three mirror, polarized 1444 nm Nd : YAG laser with intracavity PPLN was seeded by an external Nd : YAP laser at 1080 nm. Again both lasers were pumped by the fiber coupled pump modules. At 9 W pump power and optimized output coupling (1.8%) a maximum polarized fundamental output power of 330 mW at 1444 nm was generated. In a high finesse resonator, 30 W of intracavity power were estimated by measuring the output from the endmirror ($R = 99.89\%$). A beam waist of about 40 μm was created inside the PPLN crystal. The spectrum of the laser consisted of 8–
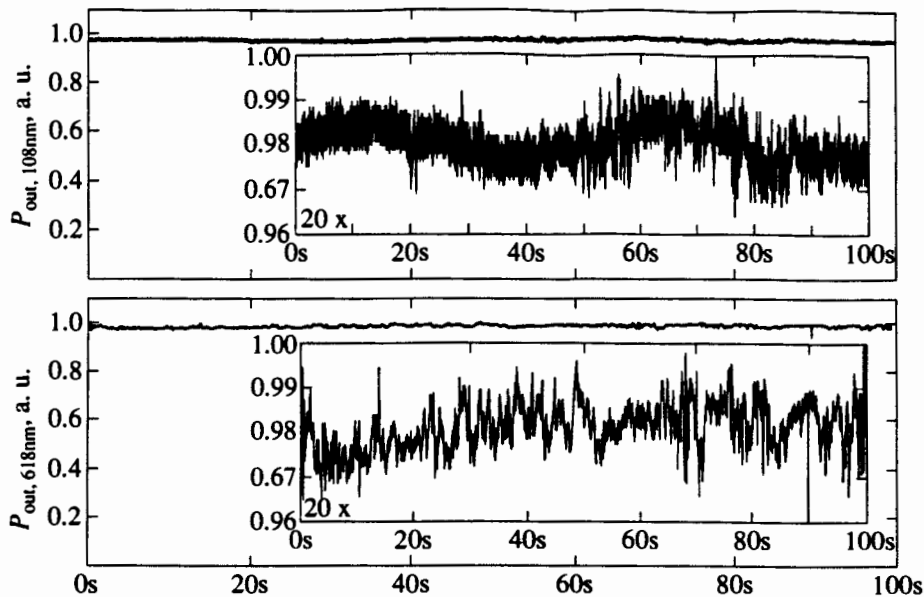
Fig. 3. Temporal behavior of intracavity power (at 1080 nm) and output power (at 618 nm) from $SR_{1080\,nm}$ SF mixer at 9 W pump power and 550 mW seeding power at 1444 nm.

9 modes, generated by spatial hole burning, equally spaced between 1443.2 and 1443.8 nm (Fig. 4). It was observed that highest output powers in the red were achieved, when the resonator was aligned for operation in a $M^2 = 1.8$ mode at 1444 nm. As a side effect, radiation at the second and third harmonic (722, 481 nm) with powers less than 5 mW were generated inside the PPLN crystal.

The 1080 nm Nd : YAP laser consisted of a three mirror resonator with an $R = 200$ mm folding mirror and an $R = 50$ mm endmirror. At 9 W pump power, up to 2.8 W at 1079.8 nm with a spectral bandwidth of $\Delta\lambda_{FWHM} = 0.4$ nm were generated (Fig. 4). The beam quality was measured as $M^2 = 1.1$. Again, this radiation was focussed through the endmirror of the 1444 nm laser into the PPLN crystal. By choosing the focal length of the lens several different beam waists of 1080 nm were generated inside the PPLN. A maximum output power of 380 mW at 2.8 W seeding power with a $\Delta\lambda_{FWHM} = 0.12$ nm was generated with a 30 μm focus (table). At highest seeding power, the intracavity power was reduced by roughly 20% to about 24 W and its spectrum was slightly shifted towards longer, not perfectly phasematched wavelengths. An input–output curve is shown in Fig. 5. The typical shape originates from intracavity power reduction due to increase of nonlinear intracavity losses with seed power.

The output power $P_{out,\,618\,nm}$ at the sum frequency can be calculated by

$$P_{out,\,618\,nm} = K \cdot P_{IC} \cdot P_{seed} \qquad (1)$$

with nonlinear coupling K, intracavity power P_{IC}, seeding power P_{seed}. The intracavity power is proportional to its output coupling loss T and internal loss L:

$$P_{IC} \propto \frac{1}{T+L} = \frac{1}{KP_{seed}+L} . \qquad (2)$$

By combining equations (1) and (2) we obtain:

$$P_{out,\,618nm} \propto \frac{1}{1 + \dfrac{L}{KP_{seed}}} . \qquad (3)$$

Estimating the nonlinear coupling from equation (1) as $K = 0.0057$ W^{-1} and assuming a linear loss $L = 2.7\%$ the fit curve in Fig. 5 is obtained.

Unfortunately, above a certain seed power level, the output showed up to 100% modulation at roughly 50 kHz (Fig. 6). We expect this to be due to high nonlinear losses and mode competition within the 1444 nm

Various combinations of fundamental laser beam waists; bold: intracavity laser beam waist

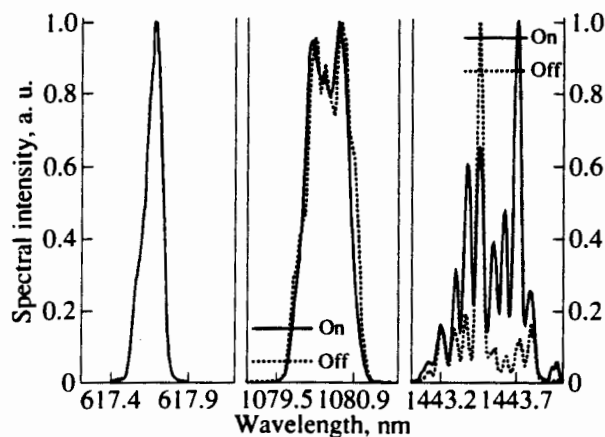| Beam waist of 1444 nm laser	Beam waist of 1080 nm laser	Output power at 618 nm
17 μm	**60 μm**	56 mW
23 μm	**60 μm**	164 mW
30 μm	**60 μm**	186 mW
48 μm	**60 μm**	117 mW
30 μm	**34 μm**	100 mW
40 μm	27 μm	353 mW
40 μm	30 μm	380 mW
40 μm	57 μm	291 mW

Fig. 4. Spectrum of the $SR_{1444\,nm}$ SF mixer and its fundamental lasers with mixer on and off; spectral resolution $\Delta\lambda < 0.02$ nm.
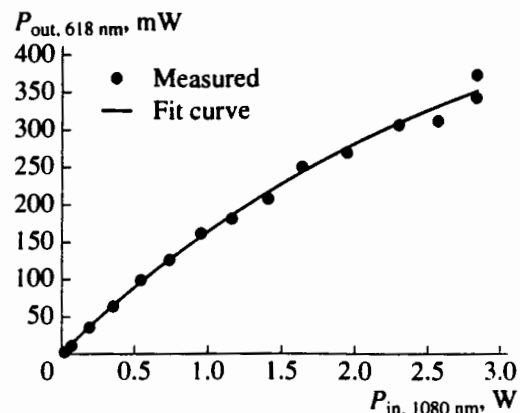
Fig. 5. Input–output curve of $SR_{1444\,nm}$ SF mixer with 9 W pump power and 30 μm (1080 nm) and 40 μm (1444 nm) beam waists.
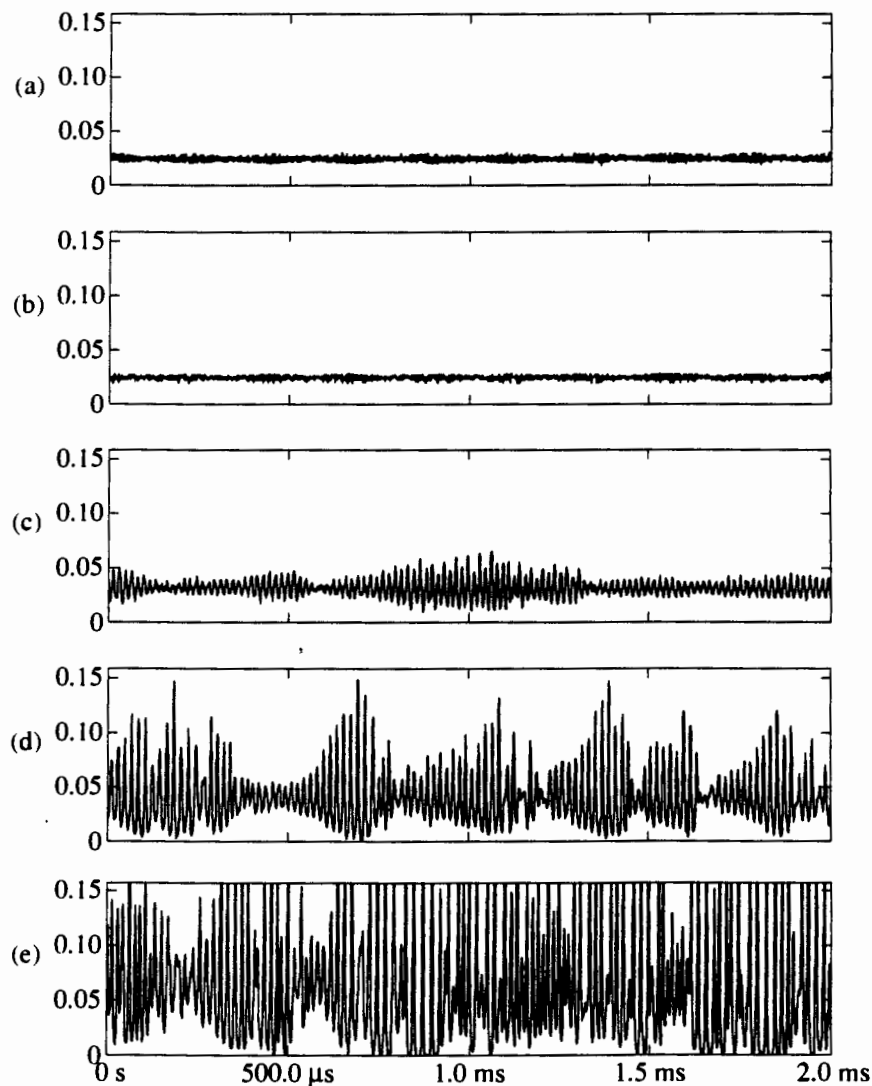

Fig. 6. Output fluctuations of $SR_{1444\,nm}$ SF mixer at 9 W pump power with various seeding powers at 1080 nm: (a) 720 mW seeding power, 125 mW output; (b) 1.16 W seeding power, 185 mW output; (c) 1.38 W seeding power, 215 mW output; (d) 1.93 W seeding power, 275 mW output; (e) 2.8 W seeding power, 380 mW output.
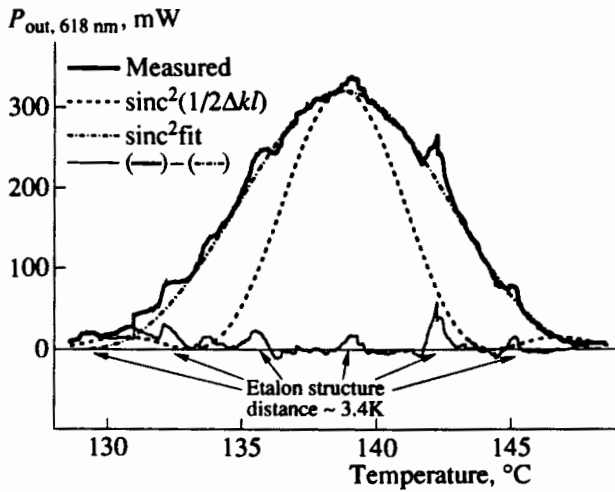
$P_{\text{out, 618 nm}}$, mW

Fig. 7. Temperature tuning curve of the $SR_{1444\ \text{nm}}\ SF$ Mixer at 9 W pumping power and 2.9 W seeding power at 1080 nm.

Nd : YAG laser. It was observed that the spectral mode distribution of the 1444 nm Nd : YAG laser changed randomly within seconds. By decreasing the seed power, the modulation amplitude was also decreased. Below 1.3 W seed power, the mixer operated continuous wave (Fig. 6).

Temperature tuning of the PPLN crystal resulted in a 8.6 K FWHM temperature bandwidth with a maximum at 139.0°C (Fig. 7). This was slightly wider than for the $SR_{1080\ \text{nm}}SF$ mixer and should originate from the spectral broadening of the 1444 nm Nd : YAG laser radiation in case of sum frequency mixing. The temper-

ature for optimized phasematching and maximum output increased by about 3 K which is an indication for smaller fundamental radiation absorption inside the PPLN compared with the $SR_{1080\ \text{nm}}SF$ mixer. Actually, in this setup no beam degradation effects were observed. The modulation on top of the fitted $\sin c^2$-shaped tuning curve is expected to be caused by an etalon effect of nonlinear crystal. The modulation period of 3.4 K coincides with a temperature induced $\Delta l = \lambda/2 = 722$ nm change in PPLN length due to thermal expansion.

Monitoring the 618 nm, red output with a fast photo diode, the operation mode of the sum frequency mixer with changing PPLN crystal temperature was measured (Fig. 8). With high nonlinear coupling inside the nonlinear crystal (between 134.3 and 143.3°C), the 1444 nm Nd : YAG laser operates, as stated above, on relaxation oscillations of about 50 kHz. Decreasing the nonlinear coupling by tuning the temperature away from phasematching, the mixer operation mode changes to pulsed operation with an offset until it finally operates continuous wave. The highest observed continuous wave output power was roughly 150 mW or about 40% of the maximum output.

In conclusion, we demonstrated a new resonator design for generation of coherent radiation in the orange to red spectral range. So far, 186 mW of truly continuous wave radiation at 618 nm were generated with this concept. The beam quality was nearly diffraction limited and the rms noise was smaller 1%. It was found that the limiting factor was the beam quality reduction of the 1080 nm laser observed at higher intensities within the PPLN crystal. In an alternative setup, higher output powers were achieved (380 mW),
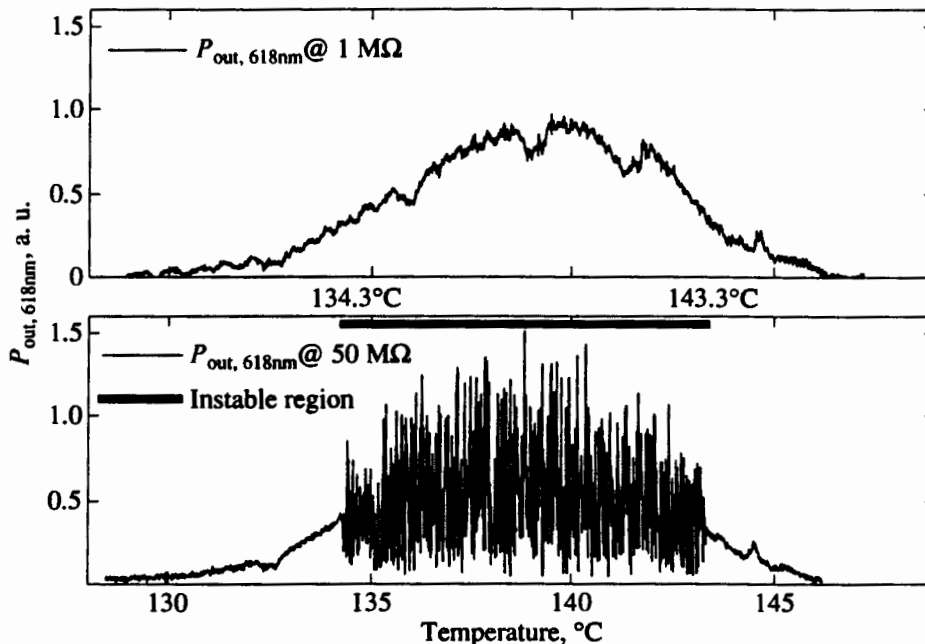

Fig. 8. Operation mode of $SR_{1444\ \text{nm}}\ SF$ mixer versus temperature at 9 W pump power and 2.9 W seeding power at 1080 nm.

however, the output was modulated by chaotic fluctuations at high nonlinear coupling and beam quality was reduced to $M^2 < 1.8$.

In general, this mixer could easily generate many other wavelengths, by keeping a high power intracavity laser and simply exchanging the low power seed laser for wavelength selection and adding a suitable poling period nonlinear crystal.

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