Extended spectral coverage of BWO combined with frequency multipliers

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Abstract: Solid state frequency multipliers extend the operating frequency range of millimeter wave Backward Wave Oscillators (BWOs) to 2.1 THz, enabling continuously tunable, narrow linewidth THz sources across the 0.1-2.1 THz range. Power conversion efficiency of frequency multipliers can be improved substantially by optimizing impedance matching between the BWOs and multipliers. Continuous improvements in solid state multiplier characteristics put the millimeter wave vacuum tubes back in fashion.

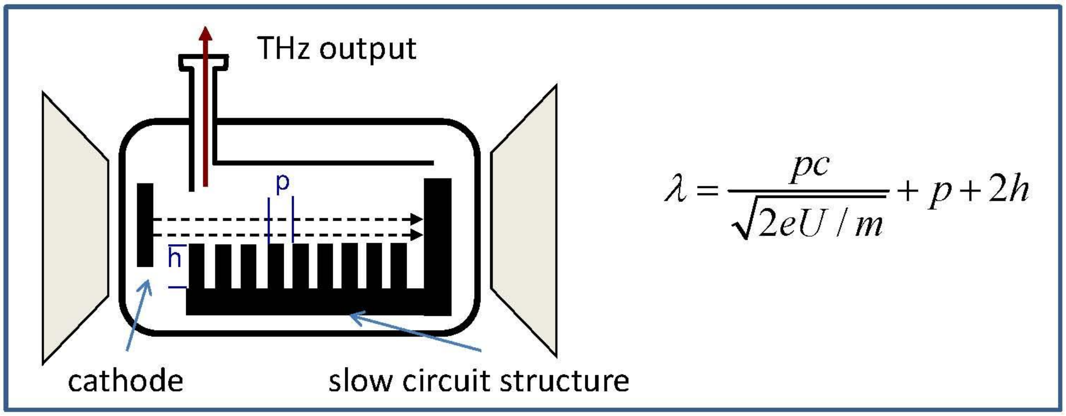
1. Introduction.

Backward Wave Oscillators (BWOs) are vacuum electronic devices that have been used for THz spectroscopy and imaging for several decades. High output power and narrow spectral linewidth, combined with frequency tunability are the main advantages of these THz sources. However, applications of BWOs remain limited to a laboratory environment and there is only one supplier of BWOs in the world, despite efforts of several vendors to start production.

Research data presented in this paper was centered on extending spectral coverage of millimeter-wave BWOs operating across 100-370 GHz range to 0.5-2.2 THz, using frequency multipliers. Millimeter wave BWOs require smaller magnets and lower operating voltages than BWOs operating at frequencies above 370 GHz, making them more practical and reliable THz sources.

2. BWO operation and characteristics.

Operation of BWOs is based on energy transfer from an electron beam to electro-magnetic wave propagating in the opposite direction. Figure 1 shows a cross-section schematic of a BWO, which includes a cathode, designed to generate high density electron beam, and anode equipped with a fine grid, referred to as slow circuit, as it slows down electromagnetic wave to match velocity of electrons in the beam. BWOs also have to be placed into a magnet to focus the electron beam just above the slow circuit. THz wave generated by the electron beam is coupled out by a waveguide.



$$\lambda = \frac{pc}{\sqrt{2eU/m}} + p + 2h$$

Figure 1: Cross-section schematic of a BWO

Wavelength of THz wave (λ) generated by a BWO is determined by the slow circuit depth (h) and period (p) and voltage (U) applied to the device. The formula shown in Figure 1 also includes fundamental constants: speed of light (c) and electron charge (e). Scaling BWO design to higher frequencies requires finer slow circuit structures, higher magnetic field, higher cathode voltage and higher cathode current density. The current density required for BWOs operating above 1 THz reach up to 150 A/cm^2, placing very stringent requirements on cathode design. Manufacturing of cathodes capable of sustaining such current density is probably the most critical part of BWO technology, which is pushing the limits of vacuum electronics.

BWO output frequency can be varied within a fairly broad range by changing cathode voltage. For example, changing voltage applied to QS2-180 (ov-86) BWO from 400 to 1500V results in frequency tuning across 100-180 GHz range, as illustrated in Figure 2 below. BWO output power also varies with applied voltage and therefore output frequency. This dependence is unique for each BWO. While the power spectrum, shown in Figure 2, may appear noisy, it is not. All the sharp peaks in the spectrum are very consistent from one frequency scan to another, enabling accurate spectroscopic measurements.

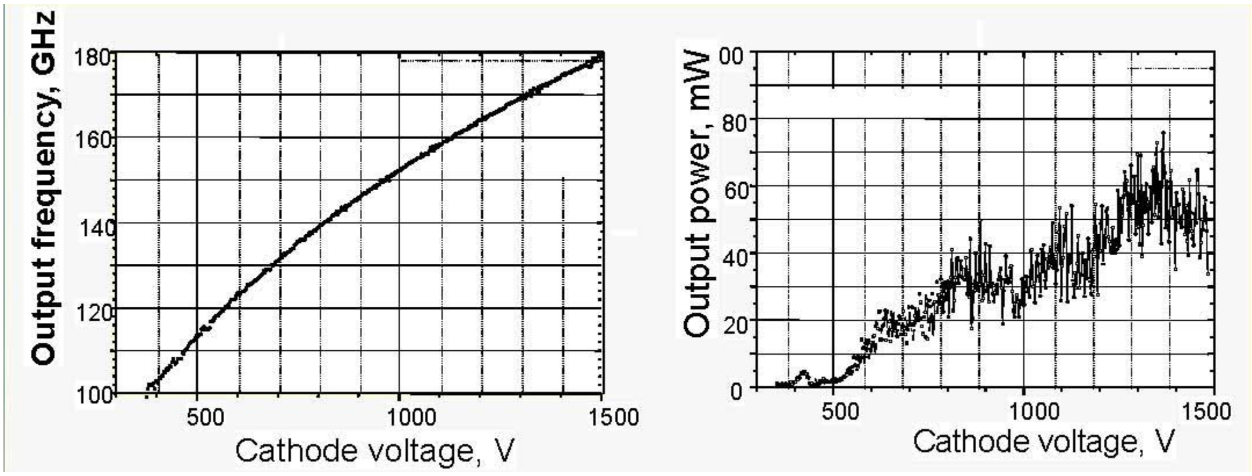


Figure 2: Typical tuning curve and output power spectrum of QS2-180 (ov-86) BWO.

QS2-180 (OV-86) BWO is one of the most popular BWO models, as it offer high power and decent tuning range, but requires relatively low voltage, comes packaged in a compact magnet and can be air cooled. All BWOs operating above 180 GHz require water cooling and larger magnets. Figure 3 shows typical output spectra of QS1-260 (ov-24) and QS1-370 (ov-30) BWOs, which are also were popular due to high power, wide tuning ranges and good reliability. However, operation of these BWOs requires voltages up to 4,000V, while cathode currents range from 25-30 mA.

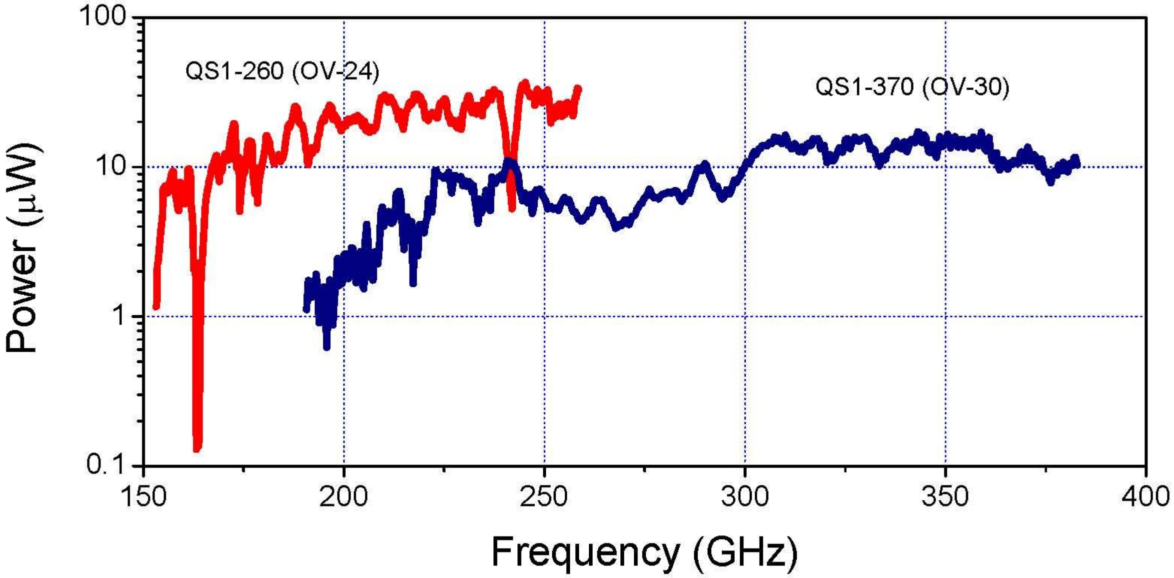


Figure 3: Output power spectra of QS1-260 (OV-24) and QS1-370 (OV-30) BWOs

Operational lifetime of BWOs operating below 400 GHz can reach up to 15 years, but it becomes limited to just a few years for BWO operating at higher frequency. Typically, the higher the output frequency, the shorted the lifetime. This is mostly due to higher cathode voltages (up to 6,000 V) and currents (35-45 mA) required on these devices, which lead to gradual degradation of the cathode. Output spectra of several high frequency BWOs are shown in Figure 4 below.

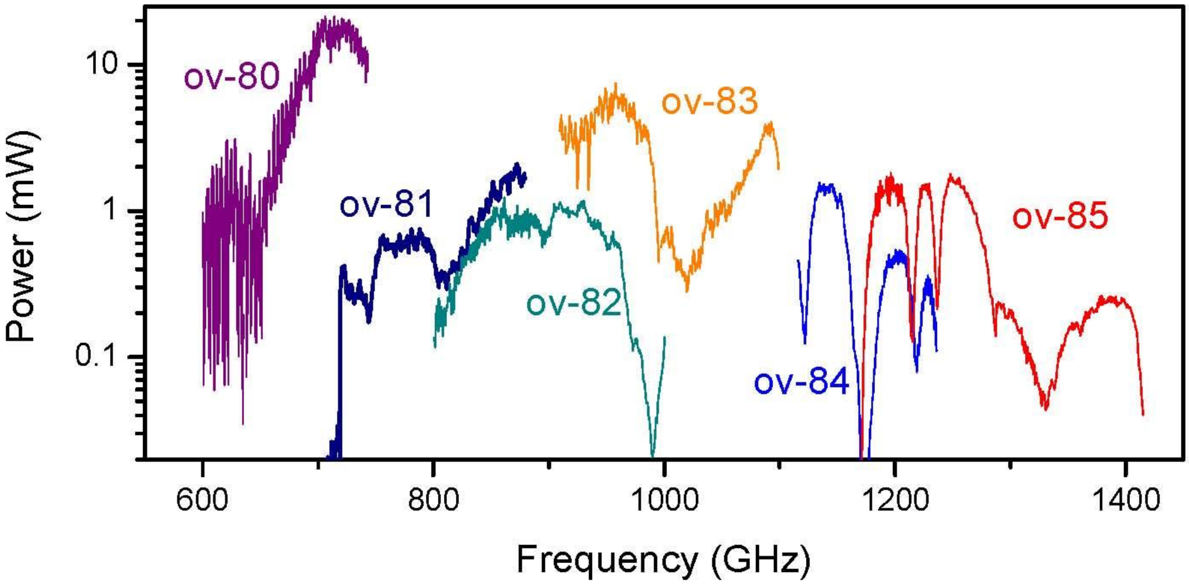


Figure 4: Typical power spectra of high frequency (sub-millimeter wave) BWOs.

Despite limited lifetime, high frequency BWOs are very powerful sources, generating up to 10 mW of power, which is necessary for most imaging and some spectroscopic applications. A more practical alternative to high frequency BWOs is offered by combining lower frequency BWOs with solid state frequency multipliers.

3. Solid-state frequency multipliers combined with BWOs

In principal, any non-linear electronic device can be used to as a frequency multiplier. However, only few devices offer reasonable conversion efficiency in THz range. Among room-temperature devices, GaAs Schottky barrier diodes are presently the best solid-state device for this application. GaAs offers an excellent combination of high mobility, sufficiently large bandgap and a fairly mature and cost effective processing technology.

Frequency multipliers rely on either variable resistance or variable capacitance of the Schottky diode to generate the higher harmonics. The main advantage of the resistive multipliers is operation over fairly broad range of frequencies. One drawback of these devices is that the theoretical maximum conversion efficiency for a xN multiplier is 1/N^2. So, for a doubler, the maximum efficiency is 25% and, for a tripler, it is 11%. Because of parasitic effects, related to frequency dependence of capacitances, series resistance and waveguide/circuit losses, typical efficiencies are 10% for doublers and 5% for triplers in 200-500 GHz range. These efficiencies decline to 0.1-0.2% at 2 THz.

Combining solid-state frequency multipliers with BWOs produced very interesting results. Figure 5 below shows output spectrum of QS-180 (OV-86) BWO tunable across 100-180 GHz range and spectra measured for a resistive doubler and tripler placed on the BWO output. Apart from operating over a very broad frequency range, these devices demonstrated larger than expected conversion efficiencies.

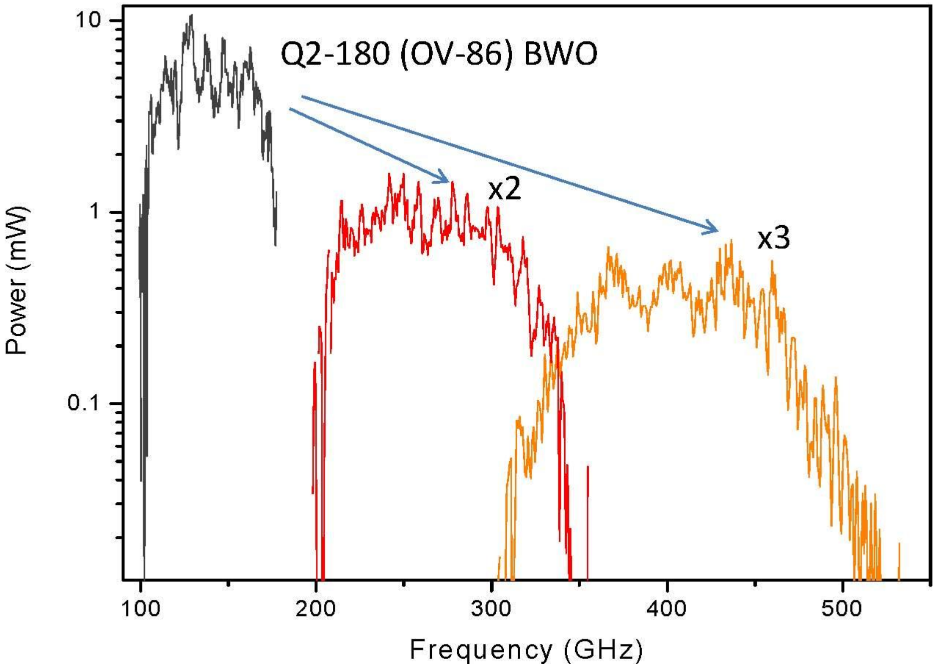


Figure 5: Output spectrum of QS2-180 (OV-86) BWO and spectra of the same device combined with a frequency doubler (x2) and tripler (x3).

Figure 6 shows power conversion efficiencies calculated for the data presented in Figure 5 along with theoretical limits for the conversion efficiency shown in blue lines. It is clear that measured conversion efficiency comes very close to the theoretical limits across most of the frequency range and even exceeds it at a few specific points. Needless to say, we calibrated frequency response of the detection scheme very carefully. We have also verified this observation on several different QS2-180 (OV-86) BWOs, using different doublers and triplers.

The only explanation to this data was that coupling of BWO output into free space less efficient than coupling it into a doubler and tripler. In other words, the multipliers help to extract more power from a BWO tham it radiates into a free space when no multipliers are attached to the output. Analyzing multiple sets of data, we noticed that very high conversion efficiencies are observed at frequencies where BWO output power is relative low, suggesting that coupling these frequencies into free space is less efficient. Also, the frequency multiplier inputs are optimized for impedance matching, so one would expect them to have an improved coupling to input THz waves. It is the magnitude of this effect that is surprising, implying that BWOs are clearly far from being optimized for impedance matching with free space.

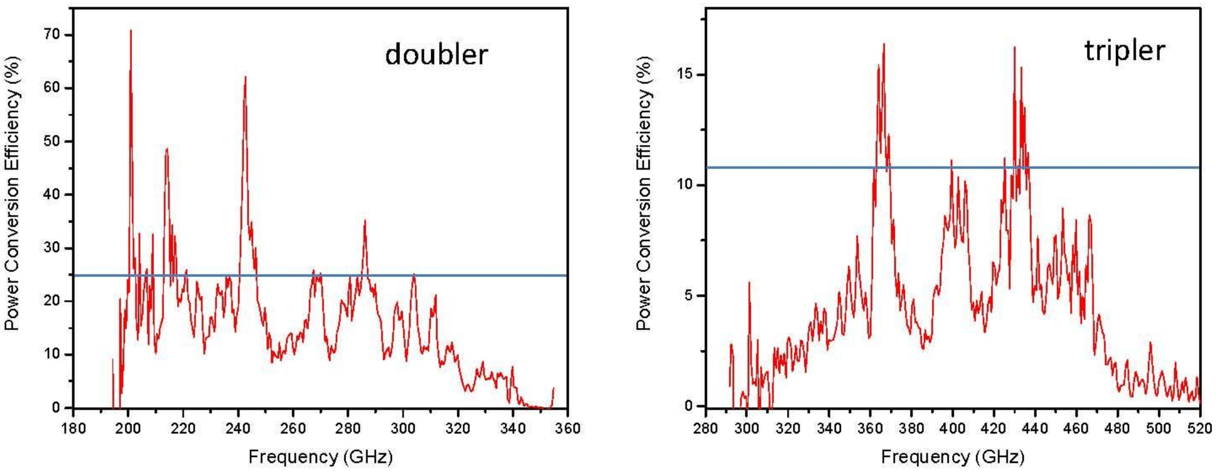


Figure 6: power conversion efficiencies of doubler and tripler calculated from data shown in Figure 5 (red lines) and corresponding theoretical limits (blue lines).

Encouraged by the extremely good performance of frequency multipliers in 200-500 GHz range, we tested higher frequency multipliers on doubled and tripled output of QS2-180 (OV-86) BWO. These data shown in Figure 7, was less surprising, as power conversion efficiency declined well below theoretical limits at higher frequencies. However, combination of QS2-180 BWO with a set of one doubler and three tirplers enables almost continuous coverage of 100-1500 GHz range. Also, the power level remains well above detection limits of sensitive THz detectors, such as Golay Cells and bolometers.

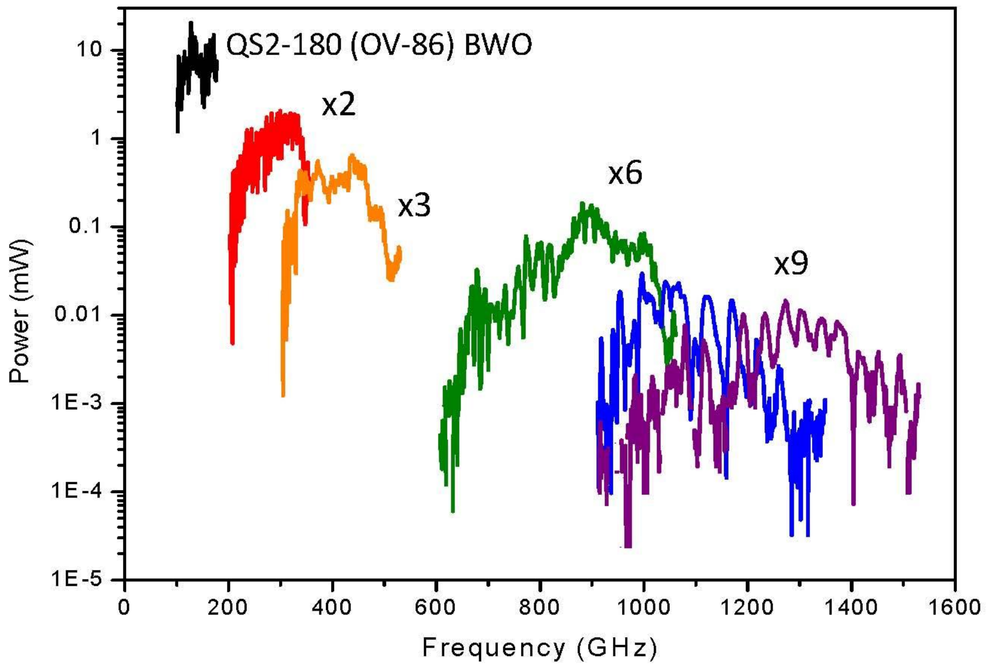


Figure 7: Output spectrum of QS2-180 (OV-86) BWO (black line) and output of this BWO combined with a set of frequency multipliers (colored lines).

Applying similar approach to extend spectral coverage of QS1 BWOs requires waveguide adapter, since these BWOs are equipped with muti-mode output waveguide and all frequency multipliers use single-mode waveguides. Transmission loss of waveguide adapters does not impact results significantly for low frequency QS1 devices such as QS1-260 (OV-24). Combination of one doubler and three triplers extends coverage of QS1-260 (OV-24) BWO to 2.2 THz, as shown in Figure 8.

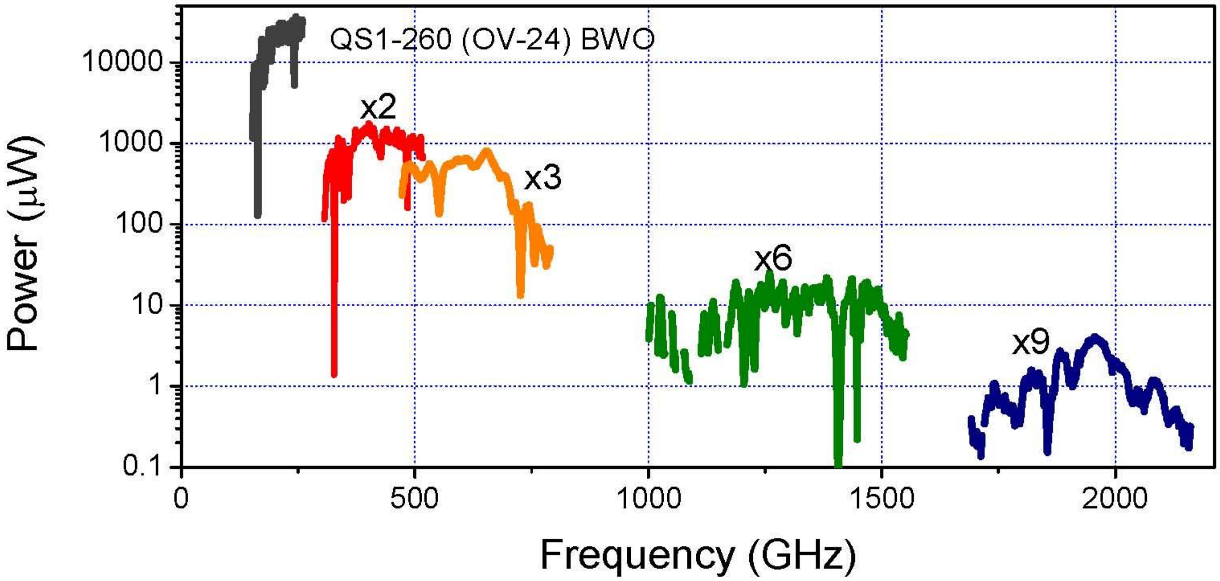


Figure 8: Spectrum of QS1-260 (OV-24) BWO (black line) and output of this BWO combined with a set of frequency multipliers (colored lines).

Transmission loss of waveguide adapters certainly becomes a problem for higher frequency devices such as QS1-710 (OV-80), as illustrated in Figure 9. Despite the high waveguide adapter loss, combination of QS1-710 with a frequency tripler enables good coverage of 1.8-2.2 THz range.

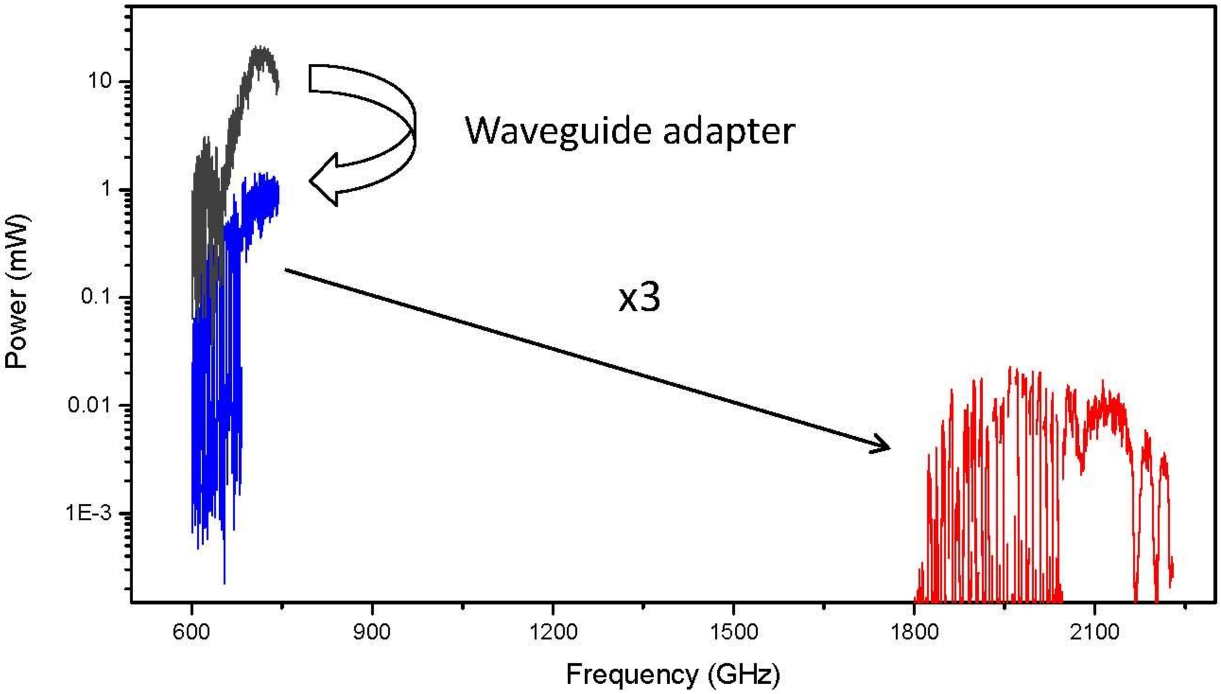


Figure 9: Spectrum of QS1-710 BWO (black line), QS1-710 BWO output measured after a waveguide adapter (blue line) and output of frequency tripler combined with QS1-710 (red line)