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ABSTRACT.

In broadband microwave reflectometry coherent detection is widely used to obtain the phase information and to improve the systems sensitivity, both in diagnostics measuring the electronic density profile and plasma fluctuations. Coherent detection uses a translated version of the probing signal to guarantee a stable Intermediate Frequency (IF). A novel technique to generate the frequency translation by double frequency conversion is here presented and its advantages over the commonly used single frequency conversion techniques employing image rejection mixers are discussed. The results obtained with the new frequency translator modules developed for three JET FM CW reflectometers, operating successfully at JET since mid 2009, are presented.

1. INTRODUCTION

A microwave reflectometer system has three main blocks: the microwave source section; the transmission line with antennae and the detection section [1]. Modern reflectometer systems measuring density profile and/or plasma turbulence of fusion plasmas use broadband oscillator sources (either frequency locked or in free run) followed by frequency multipliers. They are equipped with heterodyne receivers providing coherent quadrature detection [2,3,4,5] to obtain good sensitivity and selectivity. In large size devices like JET the reflectometers need long delay lines in the reference signal path [6] to compensate the delay due to long transmission lines. To employ heterodyne topology a Local Oscillator (LO) signal is needed. The simplest technique for to obtain the LO signal uses frequency translation employing image rejection mixers providing a single side band frequency conversion.

Here we present a novel technique for the local oscillator generation where the LO signal is generated by frequency translation using double frequency conversion. This scheme presents significant benefits over existing solutions, namely: (i) it improves the signals spectral purity; (ii) the compensation delay line can be embedded within the Frequency Translator; (iii) standard components can be used instead of high expensive special devices. The novel layout has been successfully implemented in the new JET FMCW reflectometer system (in the range 33–110GHz).

In the next sections the requirements of a heterodyne receiver for state of the art reflectometer systems are discussed and the novel solution to achieve a heterodyne coherent system using the frequency translation technique is described. The results obtained in the laboratory with the system developed for the new JET FMCW reflectometer system are displayed and the merits of the solution based on the frequency translator are discussed.

2. RECEIVER SECTION OF A MICROWAVE REFLECTOMETER

Microwave diagnostic systems for fusion plasmas should be able to detect signals with power levels below −40dBm. Since the Tangential Sensitivity (TSS) [7] of diode detectors is not sufficient to cope with such low powers (often TSS is about −45dBm in a 2MHz video bandwidth at best), modern reflectometer systems employ heterodyne receivers [8], preferably ending in quadrature detection. Usually, a tunable oscillator is utilized in the first conversion and in the final IF to baseband conversion stage a fixed oscillator is employed. To suppress the phase due to propagation in the transmission line and detect only the phase data due to the plasma, both in fixed or broadband operation, the reference signal for phase/amplitude detection must be coherent with the probing signal that was launched into the plasma. Coherent generation of signals to be used as main (RF) and Local Oscillator (LO) can be obtained in several ways: frequency conversion [9]; frequency locking of the two independent microwave sources [10]; with two independent synthesized sources both synchronized to a common reference.

For reflectometers operating at fixed frequency such as the hopping systems developed by IPFN/IST for ASDEX Upgrade and TJ-II [see reference 4], it is possible to use phase locked sources. In broadband operation such a solution cannot be adopted due to the fact that synthesized sources employing phase lock techniques do not have the ability to change its frequency fast enough for ultra fast swept operation. Frequency tracking between the two oscillators also have limits at fast sweeping (<25μsec) as they include phase locked loops. To overcome this problem several frequency conversion techniques can be adopted; the simplest one uses single side band frequency conversion. A more refined technique is here presented obtained by double frequency conversion.

3. FREQUENCY TRANSLATION BY DOUBLE CONVERSION

The technique uses a double frequency conversion arrangement (mixer and Local Oscillator) to produce a frequency shift of the incoming RF signal proportional to the frequency difference between the two reference frequencies (LO). The layout of this design is presented in figure 1. A sample of the RF signal probing the plasma is down converted in the first mixer and the resulting IF band is low pass filtered to remove the high order mixing products and the leaking RF and LO frequencies. This resulting frequency band is then up converted in the second mixer resulting in a shifted frequency band replica of the incoming band. At output, the signals are again band pass filtered to remove all the frequencies that are out of the relevant RF bandwidth. The resulting frequency shift is proportional to the frequency difference of the two reference signals.

Delay line:

As in large size devices like JET long transmission lines are needed to launch and receive the probing waves, the reflectometers must be equipped with delay lines able to compensate the long paths to the machine (at JET the delay is 270ns whereas plasma measurements are in the ns). The design and integration of the delay line in the system is an important issue for best reflectometer performance.

In the novel technique a large frequency shift is performed in both frequency conversions allowing easy filtering of the main unwanted mixer products and also enabling to embed the delay line within the frequency translation. This is not possible with a single side band frequency conversion. For the JET FM-CW reflectometers developed by IPFN three delay line sections were used (see figure 1.b). This gives the possibility to split the delay line in 3 sections and to produce the major part of the delay in the middle section that operates in low frequency (< 6GHz) therefore with much lower attenuation. This has the great advantage not only of reducing significantly the attenuation due to the delay line but it also ameliorates the delay line integration in the system. In addition, standard amplifiers and mixers can be employed instead of higher gain and slope compensation amplifiers (expensive components required by the SSBM solution) since the slope attenuation in the middle section bandwidth mirror the slope attenuation of the other two sections (see figure 1b).

Frequency translator design:

To guarantee a frequency conversion with minimum effect in the spectral components of the original RF signal, two clean reference sources were selected for the JET FM-CW reflectometers: Phase Locked Dielectric Resonator Oscillators (PLDRO) locked to a 100MHz common reference oscillator. The frequencies of the two PLDROs are higher than the maximum RF frequency to guarantee a more efficient filtering of the undesirable frequencies of the mixed (translated) signal.

The components specifications for the novel layout were derived from equations (1) to (4).

$$PLDRO1 > (RF_{\max} + IF + \Delta IF_{band}) \tag{1}$$

$$LPF_{cut} = RF_{\max} - PLDRO1 \tag{2}$$

$$PLDRO2 = PLDRO1 \pm IF / N \tag{3}$$

$$BPF = RF_{band} + (IF + \Delta IF_{band}) \tag{4}$$

In the above equations, PLDRO1 and PLDRO2 are the local oscillator sources used in the frequency converter as depicted in figure1; IF is the intermediate frequency at the reflectometer receiver section, N is the multiplication factor at the frontend and ΔIF_{band} is the expected bandwidth of the detected signal corresponding to the fringe frequency F_{fringe} variation rate. F_{fringe} is the frequency of the interference signal resulting from the interference between incident and reflected waves at the coherent detector. LPF and BPF are the bandwidth of the IF low pass filter and frequency translated signals, respectively.

The novel layout must be compatible with ultra fast broadband operation (implying broadband RF and LO operation plus very high IF bandwidth) and also to guarantee high isolation between the mixer ports to reduce the amount of resulting spurious frequencies. Triple balanced mixers were selected featuring very broadband IF response; good LO/RF to IF isolation and displaying a high reduction for the even number harmonics.

4. EXPERIMENTAL RESULTS

Table 1 summarizes the frequency requirements for the three frequency translation modules of the new FM-CW JET reflectometers operating in the frequency bands: 8 to 12GHz and 12 to 18GHz.

Table 2 displays the attenuation obtained both with a standalone delay line and an embedded 3 sections delay line. The comparison between the two solutions shows that the delay line embedded within the frequency translator has major advantages: (i) frequency equalization over the full operation bandwidth; (ii) 20dB reduction of the total attenuation.

The performance of the three frequency translator modules developed for the JET FM CW reflectometers was tested at the laboratory both in fixed frequency and fast sweep operation. The obtained results (see one example in Figure 2) show that the output translated signal has a spurious rejection level better than 35dBc across the full VCO frequency band in both modes of operation.

Figure 2 presents the signals obtained by frequency translation for the JET 12 to 18GHz modules. Spurious signals are observed only around 13.6GHz showing that with the novel technique layout the spurious are only occur at specific narrow frequency ranges. This only occurs where the frequencies resulting from a combination of high order products fall within the selected bandwidth. Input signal isolation can be higher than 100dB as it travels through both conversion sections (mixers and filters) therefore is highly attenuated. Image frequency as occur in single conversion techniques does not exist with the new topology. With single conversion topologies such as with single sideband conversion using image rejection mixers the input signal, its image conversion and the high order spurious signals are always present as sidebands of the relevant signal and can usually be suppressed by only 30dBc at most.

Figure 3 displays the ability of the novel frequency translation design to produce a clean frequency translated signal with equalized power over the full frequency band.

CONCLUSIONS

The novel frequency translation method employing double frequency translation proved to be highly flexible and robust with a much better performance (spurious signals, image rejection and isolation) than the commercial available SSBM. This is confirmed by the tree independent channels of the JET CW FM reflectometers operating successfully since mid 2009.

The delay line needed to suppress the delay due to the long transmission lines that carry the probing signals to and back to electronics can be made in several sections, the main section using a long coaxial cable embedded in the frequency translation module, which easy line integration and reduces the amplification required for frequency equalization by 20dB.

This novel design can be implemented for any octave frequency band ($2 \times F_{min} \leq F_{min}$) using only standard mixers and amplifiers instead of expensive positive gain slope amplifiers or positive slope equalizers required by single frequency conversion solutions. This makes the system development and maintenance/repair much less expensive and time consuming.

The features of the novel frequency translators and its successful implementation in JET make this development most important for future ITER reflectometers that will have to face on ITER the same type of difficulties encountered in JET.

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Frequency Requirements	8–12 GHz Translation	12–18 GHz Translation
PLDRO1 [GHz]	14.6	20.6
LPF [GHz]	9	6.6
PLDRO2 [GHz]	14.7	20.5
BPF [GHz]	7.8-13	11.6-18.6

Table 1: Selected components for the frequency translation modules used in the JET FM CW reflectometers

Frequency [GHz]	**18**	**12**	**2**	**8**
Delay 1 23.3m [dB]	23.7	18.5		
Delay 1 23.3m [dB]	27.1	21.16	7.58	16.63
Delay 1 23.3m [dB]	17.54	13.7		
Total standalone [dB]	68.34	53.35		
Total embedded [dB]	48.82	48.83		

Table 2: Total attenuation for a 3 sections delay line embedded in the JET 12 – 18 GHz frequency translator and for a standalone delay line.

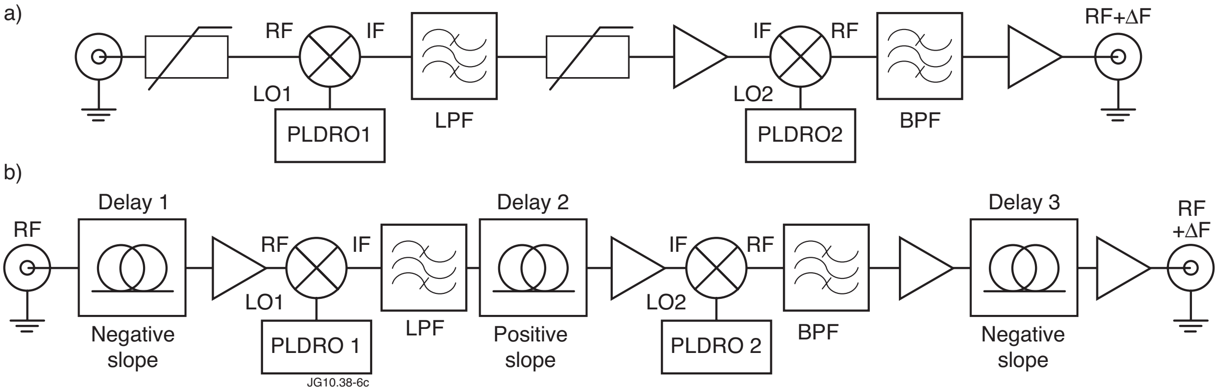

Figure 1: a) Frequency Translation scheme with double frequency conversion. b) Frequency Translation scheme with an embedded delay line as used at JET FM CW reflectometers developed by IPFN.

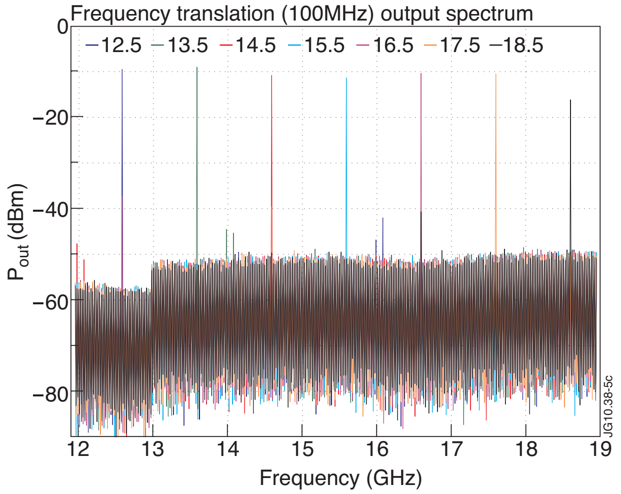

Figure 2: Signal obtained by 100MHz frequency translation for an input signal varying 12.5 to 18.5GHz. The spurious frequencies at 13.6GHz (worst case) have 35dBc.

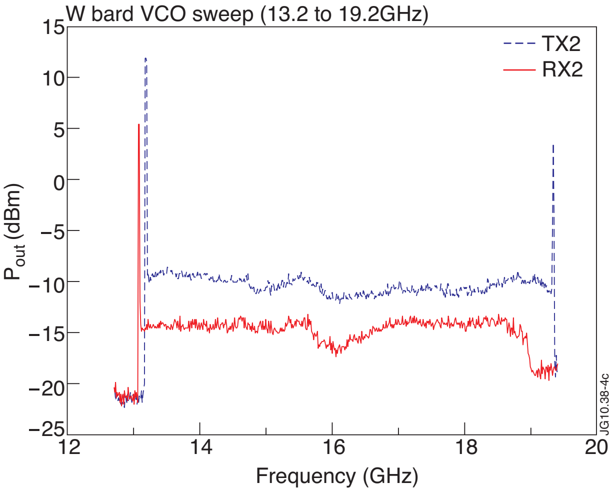

Figure 3: Output power measurements of a VCO operating in the 12 to 18.5GHz band in 20µs sweep. In blue is depicted the VCO output power used to drive the front end active.