Array of Coupled Phase-Locked Oscillators at 160 GHz

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Abstract— **A ten-channel millimeter-wave heterodyne phase measurement system is currently under construction. This system will be used for electron density measurement at the plasma experiment W7-AS. Main features are: 1) twofold usage of each 160-GHz oscillator to excite both the transmitting signal to the plasma and the local oscillator (LO) signal for downconversion and 2) the phase-locked loops (PLL's) of each oscillator are coupled in a chain. This letter describes the millimeter-wave part and the digital PLL circuits of that system. Test results of the first three channels, which are already running in the laboratory, are presented.**

I. Introduction

THE measurement of electron density is an important diagnostic tool for plasma experiments. For this purpose, a linearly polarized beam is transmitted through the magnetically confined plasma. The phase shift $\varphi = 2.82 \times 10^{-15}\lambda \int n(z)\,dz$ is introduced by the plasma [1]. Here $n(z)$ denotes the electron density and λ the wavelength of the wave travelling through the plasma. The integral is taken along the path of the probing beam and is called the line integrated electron density. In order to obtain the density distribution over the plasma cross section, it is necessary to probe the plasma along several chords. For the plasma experiment W7-AS, this is done along ten independent chords using different probing signal frequencies in the range 160–162 GHz ($\lambda \approx 1.8$ mm).

Typically, φ is measured using heterodyne systems. Reference and probing signal are downconverted and φ corresponds to the phase shift of the resulting intermediate frequency (IF) signals. Standard heterodyne systems in the millimeter-wave range have to use two different oscillators for the probing signal and as the local oscillator (LO) source for downconversion.

An array of phase-locked oscillators can significantly reduce the number of oscillators needed in a multichannel system. The oscillators of an array may run at one single frequency [2] or on frequencies equally spaced on the frequency axis [3]. The oscillating frequencies of the array described in that paper are not equally spaced.

II. Principle of Operation

The principle of arraying phase-locked oscillators can establish a chain of synchronized oscillators, which are not necessarily equidistantly spaced on the frequency axis. Let $f(k) (k = 0, 1, \cdots, N)$ denote the frequency of the kth oscillator. It is possible to achieve $f(k+1) - f(k) \neq f(k) - f(k-1)$ and $f(k+1) - f(k) \neq |f(k \pm n) - f(k)|$, $n = 2, \cdots, N$. This means that narrowband amplifiers operating at intermediate frequencies $\mathrm{IF}(k) = f(k+1) - f(k)$, $k \neq N$ process only first-order mixing products of oscillators $k+1$ and k, which are directly neighbored on the frequency axis. As a consequence, the IF processing of the kth channel is not disturbed by any other mixing product. This arrangement is used to measure the phase shift introduced by a magnetically confined plasma with ten different independent probing beams, $N = 10$. Each of the oscillators running at $f(k)$, $k > 0$ are used as the probing signal, which travels through the plasma, and as LO for downconversion of the next subsequent probing signal. The oscillator at $f(0)$ is used as LO only. As the plasma is kept in a metallic vacuum vessel, numerous crosstalk and multiply-reflected signals will appear at each receiver input. Due to the characteristic of the frequency spacing, these signals are suppressed by the narrowband IF amplifiers.

III. Millimeter-Wave Part

Millimeter-wave signal sources and receiving mixers are shown schematically in Fig. 1. Gunn oscillators with doublers are used to generate both probing signal and the LO signal for downconversion of the received signal of the next subsequent channel. The Gunn oscillators are running in the 80-GHz frequency range and deliver an output power of 40 mW. The frequency doubler efficiency of 10% results in an output power of 4 mW in the 160-GHz frequency range. This signal is used as the probing signal and is fed to the plasma. A tenth part of the probing signal is separated by a directional coupler and drives the receiving mixer of the next subsequent channel (see Fig. 1). Having passed the plasma, the probing signal is downconverted to an IF in the range 120–210 MHz. This conversion is performed by a single-ended Schottky-diode mixer, which is driven by the doubled Gunn oscillator signal of the previous channel. The master oscillator, which is also shown in Fig. 1, generates the LO signal for the first channel.

A crossguide directional coupler is mounted in between the Gunn oscillator and the doubler, thus giving access to the oscillator fundamental signal. This signal is mixed with the fundamental Gunn signal of the previous stage. The resulting IF signal is fed to a phase-locked loop (PLL) circuit (see Section V) and to the reference signal output. The fundamental master oscillator signal is downconverted by use of a harmonic mixer driven by a fixed-frequency 7980-MHz oscillator. The resulting IF is also fed to a PLL. It should be noted that the frequency of the IF resulting from the probing signal is twice

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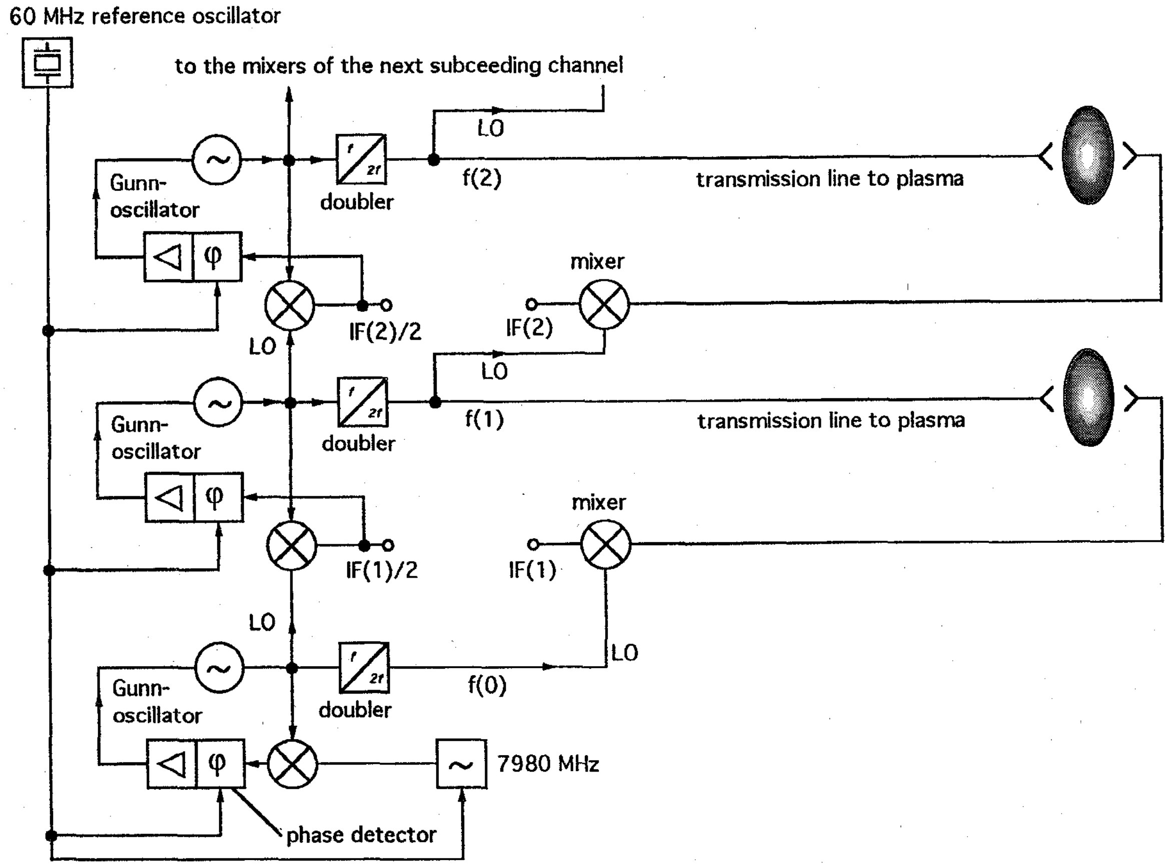

Fig. 1. Schematic view of the array of phase-locked Gunn oscillators. For simplicity, only the first two oscillators are shown.

TABLE I
PROBING SIGNAL FREQUENCY f AND INTERMEDIATE FREQUENCY IF FOR CHANNEL k. THE MASTER OSCILLATOR FREQUENCY IS 159.90 GHz

k	1	2	3	4	5	6	7	8	9	10
f/GHz	160.02	160.15	160.29	160.44	160.60	160.77	160.95	161.14	161.34	161.55
IF/MHz	120	130	140	150	160	170	180	190	200	210

the reference IF. Due to this fact, the probing signal IF has to be divided by two before performing the phase measurement.

The twofold usage of the oscillators for both probing and LO signal limits the number of millimeter-wave sources: 11 Gunn oscillators are needed for 10 heterodyne channels.

The oscillating frequency of different channels is offset by appropriate setting of the PLL circuits. The probing signal frequencies and the resulting IF's for the set of ten channels are summarized in Table I.

IV. PHASE-LOCKING ELECTRONICS

Phase-locked loops for all oscillators increase the frequency stability of the probing signals. Source frequency stability is of particular importance if the path lengths of probing and reference signal are not equal. Let ΔL denote the total path difference between probing and reference signal. Phase shift $\delta\varphi$ due to frequency fluctuation δf is given by $\delta\varphi{=}2\pi\delta f\,\Delta L/c$, where c denotes the velocity of light. To achieve $\delta\varphi$ less than 1% of the overall measurement range for $\Delta L = 50$ m, a relative frequency stability of $\delta f/f < 4 \times 10^{-6}$ is needed. First experiments show that $\Delta f/f < 10^{-6}$ is possible using PLL circuits.

The PLL circuits of the individual Gunn oscillators form a chain. Each oscillator signal to be locked is downconverted to a low IF by use of the preceding phase locked Gunn as the LO signal (see Figs. 1 and 2). Phase jitter builds up along the chain of PLL's. This characteristic is similar to a cascade of digital repeaters, where the clock is recovered by a PLL [4], [5]. Two different failure phenomena can be observed. 1) Any additive noise or interference with other electronic circuits or instability of a PLL leads to phase or frequency modulation of the corresponding oscillator. The same modulation is introduced to the following oscillators. 2) Consider the kth oscillator drifts out of the capture range of its PLL. This oscillator is now free running and after doubling the frequency offset $f(k) - f(k-1)$ from the preceding oscillator is no longer fixed. The subsequent oscillators are still locked.

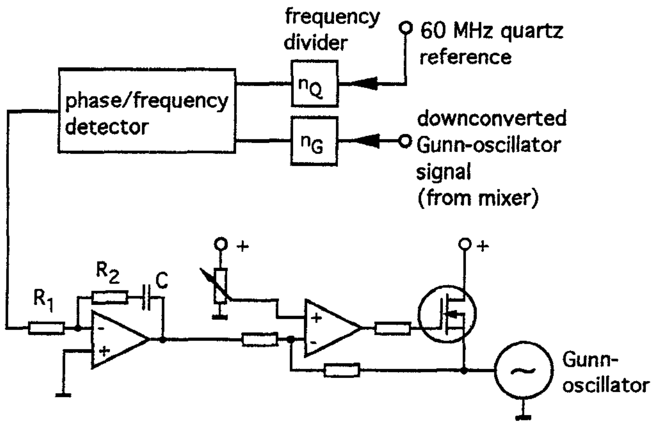

Fig. 2. Simplified scheme of the phase-locking electronics.

Keeping the offset $f(k+1) - f(k)$ constant, these oscillators track $f(k)$.

Each oscillator running at the fundamental $f(k)/2$ in the chain is mixed with the oscillator at $f(k-1)/2$ in the previous stage (see Fig. 1). Isolators and directional couplers (these elements are not shown in Fig. 1 for simplicity) in the mm-wave part make sure, that no other signals are involved in this conversion process. Therefore, the PLL for the oscillator at $f(k)/2$ is not disturbed by any oscillator in the chain, though the locking range of 150 MHz typically is larger than the frequency distances given in the Tables.

Fig. 2 gives a simplified view of the PLL. The frequency or phase of the Gunn-oscillator is controlled by changing the Gunn bias voltage. The phase-locking electronic essentially consists of an integrated circuit containing the digital phase/frequency detector and programmable frequency dividers for the quartz reference signal and the downconverted Gunn-oscillator signal to be locked [6]. The frequencies given in Table I are achieved by appropriate setting of the divide ratios n_q and n_g.

The output signal of the phase/frequency detector is integrated (see Fig. 2). The resulting control voltage is combined with the fixed Gunn-bias voltage in a current source, similar to a circuit suggested by [7].

Using standard theory [8] for a second order PLL the damping factor ζ turns out to be in the range $2 < \zeta < 6$. This coincides with the requirement for rather high ζ to minimize the buildup of phase jitter in a chain of PLL synchronizers [3], [4].

V. Experimental Results

The first three channels ($N = 3$) of the system have been successfully tested in the laboratory. Stable operation of all PLL's could be achieved. No spurious modulation related with phase jitter accumulation in the chain of PLL's has been observed. By using isolators in the millimeter-wave signal paths direct coupling and injection locking of the Gunn oscillators could be avoided. The downconverted spectrum of the third Gunn oscillator ($k = 3$) is shown in Fig. 3. The line shape of the downconverted signal is masked by the internal filter of the spectrum analyzer. The resolution bandwidth of the spectrum analyzer is 1 kHz. This means that the relative frequency stability $\delta f/f$ is at least 10^{-6}. The spectra of the preceding oscillators ($k = 0, 1, 2$) look nearly identical to Fig. 3.

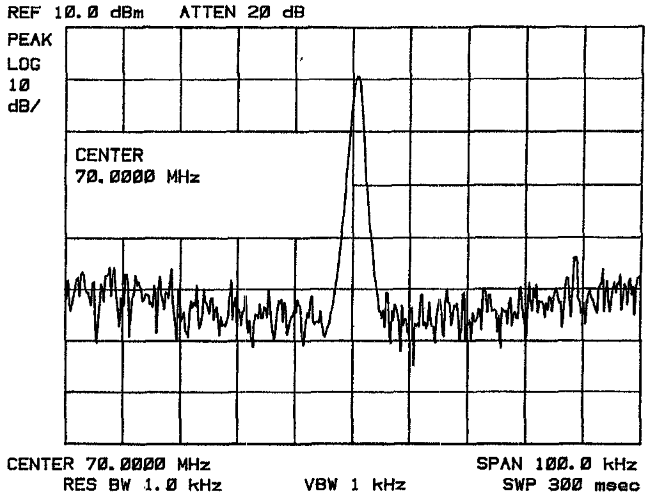

Fig. 3. Spectrum of the downconverted 80.145-GHz fundamental signal of the channel three-Gunn oscillator. Resolution bandwidth is 1 kHz. Vertical scale: 10 dB/div.; horizontal scale: 10 kHz/div.

VI. Conclusion

A principle of coupling phase-locked oscillators was introduced, synchronizing each oscillator at frequencies that are not equally spaced on the frequency axis. This principle is used to establish a ten-channel heterodyne phase measurement system, operating in the 160-GHz frequency range. The number of oscillators needed for N channels could be reduced to $N + 1$ (in contrast to $2N$ for standard arrangement). Encouraging results with the first three channels have been achieved. It is expected to operate the full system successfully in the near future.

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