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Production of sinusoidally modulated electron beams of high spectral purity*

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This paper describes a system for producing sinusoidally modulated electron beams with cancelled second-harmonic content. The system consists of a predistortion synthesizer, a high-voltage coupling transformer, and a current modulator circuit for a gridded gun. Despite the nonlinear effects inherent in electron beam transport systems, second-harmonic contamination levels at the target have been suppressed to ~ 100 ppm. Such beam modulation permits sensitive measurements of the linearity of the beam–target interaction.

I. INTRODUCTION

Several physical investigations involve the irradiation of a target with an electron beam in conjunction with the simultaneous measurement of a response. The linearity of the target response to the electron excitation can be probed using frequency-domain methods and the fact that a strictly linear system, under strictly sinusoidal excitation, will yield a response which contains only the fundamental and no harmonic components. Thus, the extent to which the target response deviates from linearity can be accurately determined from the relative harmonic content of the response. However, the harmonic content of the electron beam modulation must be negligible in order to apply this method.

The harmonic linearity method has applications in which significant information can be obtained specifically from knowledge of the sign and magnitude of the second-order term in the target response. For example, it has been proposed[1] that the linearity of beam-induced target current in scanning electron microscope studies of semiconductors could be used to correlate visible defects with the presence of potential barriers or microscopic p–n junctions. In addition, harmonic linearity methods have been successfully applied in cathodoluminescence experiments[2] where they have yielded information on the nature of luminescence bands and the physical mechanisms associated with the introduction of quenching defects by ion implantation. Figure 1 illustrates the origin of second-harmonic generation in the luminescence experiment for cases in which the target response is sublinear or superlinear. The generality of harmonic linearity methods suggests that other applications will be developed in the future.

This paper describes a system capable of producing current-modulated electron beams with second-harmonic content of approximately 100 ppm. The basic approach is to design the most stable and linear modulation system possible and then employ appropriate predistortion of the modulating signal to cancel the second-harmonic component of beam current at the target. The apparatus described is useful from low audio frequencies to the MHz region.

II. APPARATUS

The modulating system consists of a harmonic predistortion synthesizer, a high-voltage coupling transformer with secondary at cathode potential, and an electron gun modulator circuit. Figure 2 illustrates the use of the modulating system components in conjunction with a small electron accelerator employed for cathodoluminescence measurements.[2] The modulating signal originates in the reference oscillator which is at fundamental frequency. This oscillator also furnishes the phase reference for synchronous detection of the target response. The distortion synthesizer generates a synchronous second-harmonic signal which is internally mixed with the fundamental. The output of the distortion synthesizer is a predistorted signal which contains a second-harmonic component whose amplitude and phase can be adjusted relative to the fundamental. Following amplification, the predistorted signal is passed through a high-voltage coupling transformer to the electron gun modulator which floats at beam potential. The modulator drives the gridded gun of the accelerator

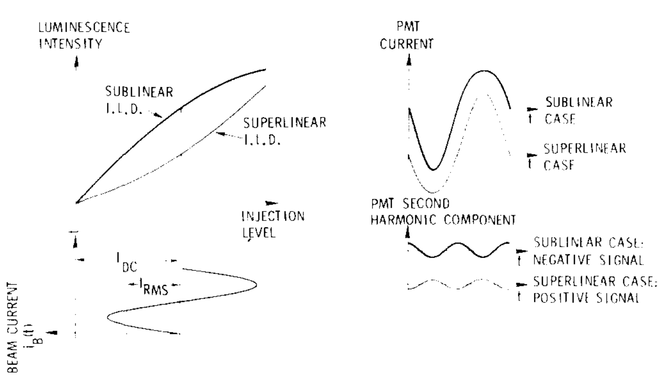

FIG. 1. Illustrating the origin of nonlinearity-induced second-harmonic signals in target response in a cathodoluminescence experiment. The departure from a linear injection level dependence (ILD) gives rise to harmonic signals that differ in phase depending on whether the ILD is sublinear or superlinear.

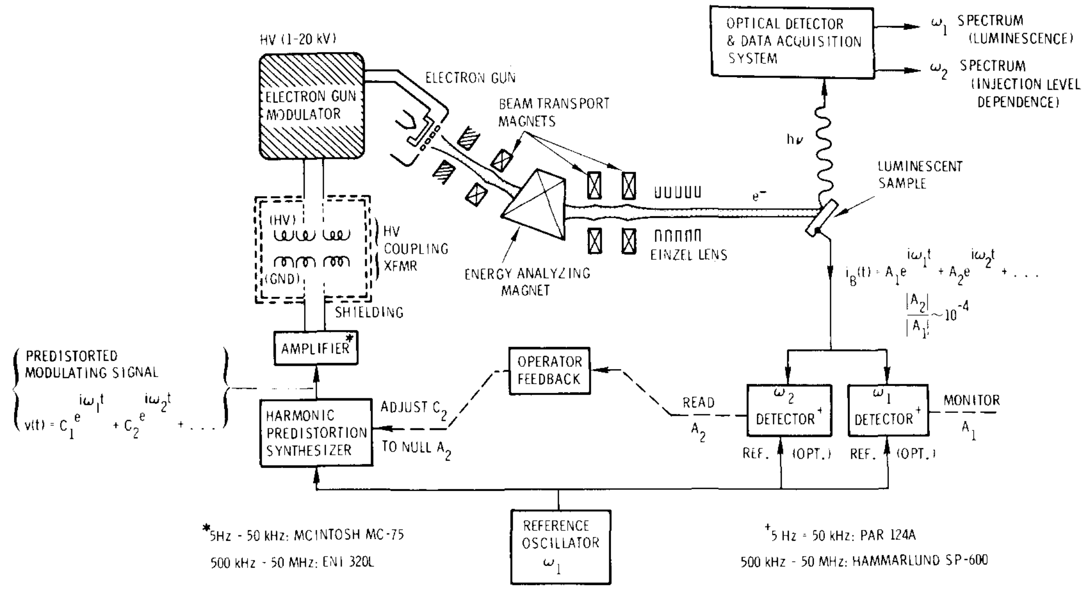

FIG. 2. Modulation system used with 1–20 keV electron accelerator to produce harmonic-neutralized electron beams. The beam transport magnets, energy analyzing magnet, and einzel lens are components of the accelerator system.

with a cathode current proportional to the voltage received from the coupling transformer.

The components of the modulating system are described next. Figure 3 shows the schematic diagram of the distortion synthesizer unit. The input signal at frequency ω_1 is shifted in phase by a combination of fixed (R1, R2, C1, C2) and variable (R3, R4, C3, C4) RC phase shifters which cover ranges of $\pm 45°$ and $\pm 90°$, respectively, at frequency ω_1. The phase-shifted fundamental is amplified by Q5–Q10 and then full-wave rectified by CR1–CR4. The rectified fundamental is rich in second-harmonic content, which is selected by the bandpass filter N1 tuned to the second-harmonic frequency ω_2. After further amplification by Q14–Q16, the second-harmonic signal is summed with the fundamental input by means of T3 and the amplifier chain Q17–Q20. Overall oscillations cannot occur around the harmonic-forming loop because the input impedance at Q17 is much greater than the impedance of the potentiometers R7–R8 at the other side of the T3 secondary. The distortion synthesizer output thus consists of the fundamental signal with an added second-harmonic component adjustable in relative amplitude and phase. Note that the conversion from ω_1 to ω_2 effectively doubles the phase range of the RC phase shifters, so that all possible phase relationships are available. Finally, we mention that the unusual emitter-coupled transistor pairs chosen for general use in the distortion

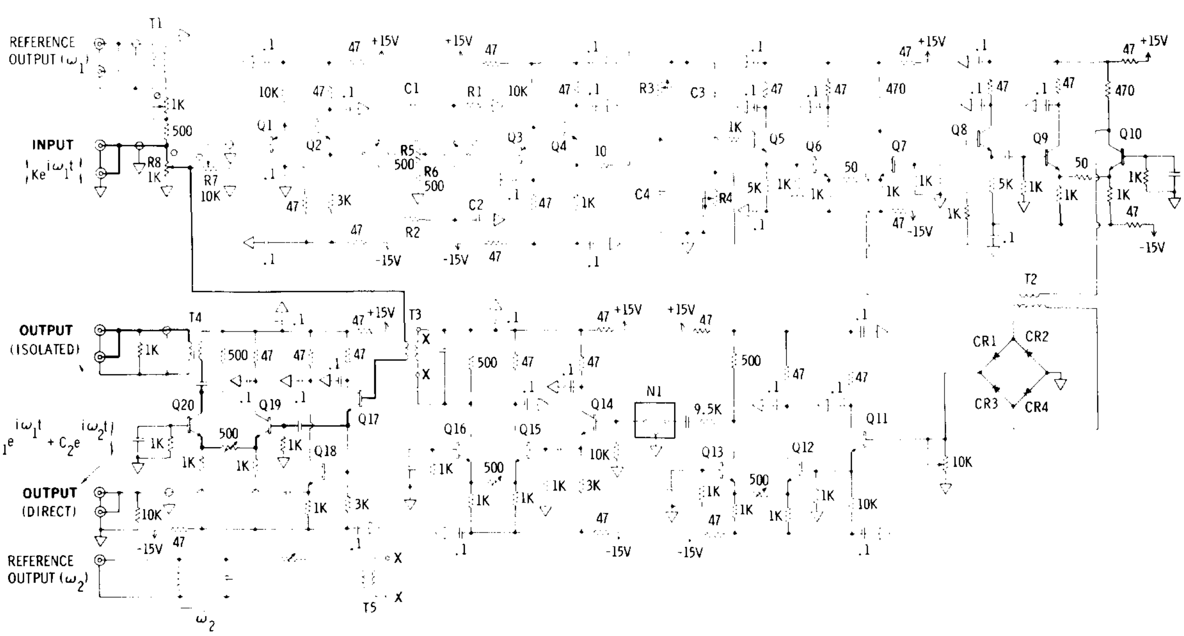

FIG. 3. Schematic diagram of distortion synthesizer. Transformers and unlabeled capacitors are chosen according to operating frequency.

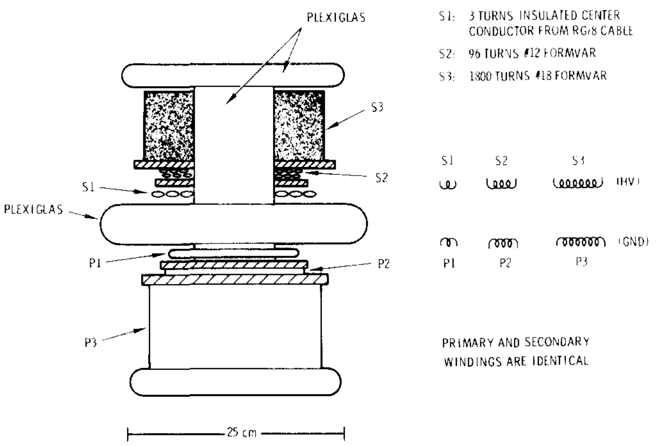

FIG. 4. Wideband transformer designed for coupling modulating signals across high voltage.

synthesizer are quite stable with inductive loads and are useful at frequencies from hertz to tens of megahertz with appropriate transformers.

The signal from the distortion synthesizer is amplified and fed to one primary of the high-voltage coupling transformer described in Fig. 4. Despite the cumbersome nature of a transformer for low audio frequencies, it was deemed essential to employ transformer coupling across the high voltage because of the temperature drift and inherent nonlinearity of optical coupling methods. Also, the transformer is an air-core unit to avoid the nonlinear effects associated with magnetic materials. The primary and secondary of the coupling transformer each consist of three windings which are selected according to the desired frequency range. In this way the transformer in Fig. 4 is capable of coupling signals at frequencies from 5 Hz to beyond 100 MHz.

The electron gun modulator is described in Fig. 5. The incoming signal from the secondary of the coupling transformer is $\sim$0.1 V in amplitude but contains 60-Hz interference and noise. At frequencies of hertz to kilohertz, the ω_1 and ω_2 signals are filtered and amplified by the input circuitry shown in Fig. 5. Input filtering is not used at megahertz frequencies. The resulting voltage signal at amplifier output is converted to a proportional current by R100, which faces a low impedance at the emitter of Q100. This modulated current appears in the high-impedance tuned collector circuit and, in turn, modulates the cathode current of the electron gun operated in grounded-grid configuration. The use of cathode current modulation is important as it avoids the severe nonlinearity of the $I = kV^{3/2}$ characteristic of a gridded electron gun. The dc cathode current is stabilized separately by a constant-current source. The modulator circuit shown in Fig. 5 has been used at frequencies from 5 Hz to 5 MHz.

III. OPERATION

Adjustment of the phase and amplitude controls is facilitated by first determining the phase of the intrinsic second-harmonic distortion in the accelerator system. Then, with the ω_2 beam detector set at 90° to this phase, the predistortion signal is applied and its phase set opposite to that of the inherent distortion. Next, the ω_2 beam detector is set at 0° and the amplitude of the predistortion signal is adjusted to cancel the harmonic signal on the beam. After several iterations, this process will yield harmonic cancellation for all phases of second harmonic. With our accelerator system second-harmonic contents of 100 ppm are routinely achieved. In fact, the beam harmonic content is far less than the harmonic distortion originating from the reference

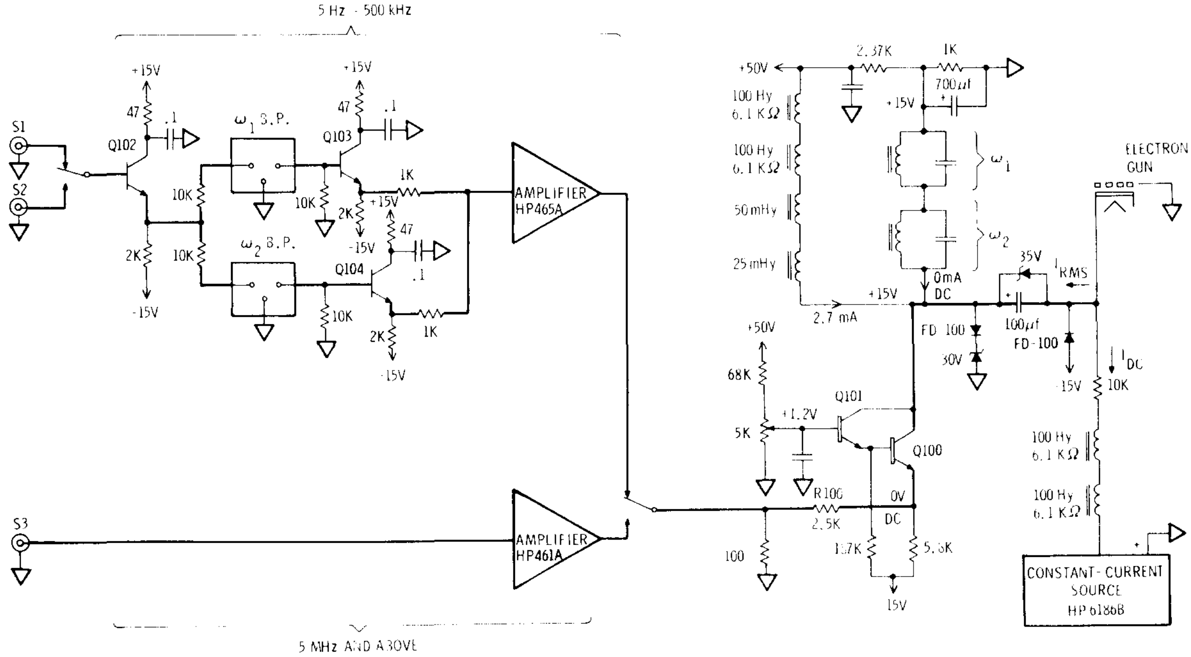

FIG. 5. Schematic diagram of electron gun modulator.

oscillator. The high spectral purity of the beam modulation permits harmonic linearity measurements that are quite sensitive compared to straightforward methods. In our case, it appears that accelerator stability is the primary factor which limits further reduction of harmonic contamination.

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