Evaluation of the Modulation Performance of Injection-Locked Continuous-Wave Magnetrons

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***Abstract*—This paper proves that 2.45- and 5.8-GHz band continuous-wave magnetrons can be used to perform amplitude, phase, and frequency modulations by applying an injection-locking method. The magnetron behaved like an amplifier, and its output could follow the injection signal. In addition, we have achieved the transmission of amplitude-shift keying data at 200 kb/s as well as phase-shift keying and frequency-shift keying at 10 Mb/s. Moreover, we quantitatively discussed several demodulation performances of the injection-locked magnetrons. Finally, the transmission of audio and video information was demodulated using the injection-locked magnetrons.**

***Index Terms*—Amplitude-shift keying (ASK), frequency-shift keying (FSK), injection locking, magnetrons, modulation, phase-shift keying (PSK).**

I. Introduction

CONTINUOUS-WAVE magnetrons are extensively used in heating applications, e.g., microwave ovens. The advantages of magnetrons include low-cost, high-efficiency, and high-level output. However, when magnetrons are used as transmitters, they exhibit several shortcomings such as an unstable output frequency and high levels of phase noise [1]. Several studies have investigated magnetron noise. For example, a study conducted by our research group examined the magnetron noise and developed a phase-controlled magnetron (PCM) [2]. Furthermore, we developed a kilowatt)-class high-power phased array system for wireless power transfer (WPT) that can be referred to as a space power radio transmission system and a power-variable PCM for the WPT systems [3]–[5]. Liu *et al*. [6] established a phase-locking 15-kW magnetron for coherent power combining. Tahir *et al.* [7] have achieved frequency and phase modulations using an injection-locked 2.45-GHz magnetron as a transmitter for communication in which the transmission of phase-shift keying (PSK) data was achieved at 2 Mb/s. In their study, a fast p-i-n diode switch was used to drive two RF sources in the modulation system, which discontinued the phase of the frequency-shift keying (FSK) signal that caused unnecessary spectrum radiation.

In addition, several studies have explored 2.45-GHz injection-locked magnetrons using the phase-locking method by controlling the anode current at low noise levels [1]–[7]. In this method, the output power of the magnetron is observed to change with the anode current, which requires a linear relation between the anode current and the oscillation frequency of the magnetron. However, a 5.8-GHz magnetron exhibits different frequency–current characteristics compared to a 2.45-GHz magnetron. Therefore, our group has addressed this problem in a previous study by developing a 5.8-GHz PCM by controlling the phase of the injection signal to lock the magnetron phase [8]. Our study was necessary to verify the modulation system based on the performances of different magnetrons.

Another study developed a 1-kW class microwave band solid-state amplifier with an eight-way combiner to replace the vacuum tube devices [9]. Similarly, Hasegawa *et al.* [10] have developed a 170-W high-efficiency amplifier. Recently, extensive research has been conducted on high-power amplifiers in the microwave band [11]–[13]. In these studies, the amplifiers were combined by N-way combiners to improve the output, which may increase the cost and complicate the manufacturing process.

In this paper, a high versatility injection-locked magnetron system, which can be applied to 2.45 GHz as well as the 5.8-GHz magnetrons and act as a communication transmitter for amplitude-shift keying (ASK), PSK, and FSK, was developed. In addition, a modulating signal was injected into the magnetron to amplify it. This method was also used to verify the transmission of the ASK data at 200 kb/s as well as the PSK and FSK data at 10 Mb/s. Moreover, the audio and video data were modulated on a magnetron output and were further demodulated to evaluate the modulation performance of the injection-locked magnetron.

II. Magnetron Characteristics

The injection locking method of magnetrons is injecting a signal into the magnetron to lock the oscillation frequency. The value of the injection signal frequency is set to be close to that of the self-oscillation frequency of the magnetron. The locked

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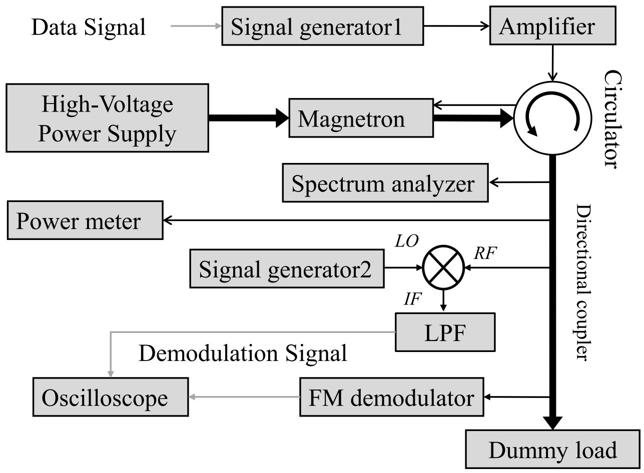

Fig. 1. Experimental system of the injection-locked magnetron.

frequency range Δf can be expressed by Alder equation [14] as follows: $\Delta f = 2f(P_i/P_o)^{1/2}/Qe$, where f is the injection signal frequency, P_i is the injection signal power, P_o is the magnetron output power, and Qe is the external Q-factor of the magnetron.

In the locked frequency range, the frequency and phase of the magnetron output are locked with the injection signal. Therefore, controlling the parameter of the injection signal results in the frequency and phase synchronization of the magnetron output. In addition, the injection of a modulating signal allows the magnetron output to follow the injection signal and to amplify the modulating signal.

This paper intended to develop a highly versatile modulation system, which can be applied to the 2.45- and 5.8-GHz band magnetrons. However, the study mainly evaluated the modulation performance of the 5.8-GHz band magnetron because it has a different performance and exhibits a higher noise level than the 2.45-GHz band magnetron [8].

Fig. 1 illustrates an experimental system of the injection-locked magnetron modulation. The system comprises a signal generator (signal generator 1, Agilent N5183A), which injects a signal into the magnetron via an amplifier and a circulator. The injection signal frequency exhibits the same value compared to the value of the self-oscillation frequency of the magnetron. During the experiments, the injection signal was sufficiently amplified to lock the magnetron frequency, and the magnetron output was measured via a directional coupler, whose output was connected to a dummy load. The experimental conditions of the magnetrons are presented in Table I. The locked frequency range Δf was measured with a spectrum analyzer (Agilent N9010A) using a directional coupler signal (results are illustrated in Fig. 2). According to the Alder equation, a large Δf value can be obtained for both the 2.45- and 5.8-GHz band magnetrons by increasing the injection power.

III. Modulation Performance Evaluation Experiment

A. Injection-Locked Magnetron for ASK

The output power of a magnetron can be changed using four methods that involve controlling one of the following parameters: 1) anode current [8]; 2) magnetic field [5], [15], [16]; 3) filament power; and 4) injection power. Therefore, adjusting one of these parameters can modulate an ASK signal.

In the first method, a high-voltage power supply (Glassman PS/LT005R360-20) was used to control the anode current of the magnetron. It was observed that the rise time of the high-voltage power supply was approximately 3 ms. However, a pulsed-driven power supply can improve the rise time to 0.1 ms [17]. In this case, the rise time of the power supply limits the data rate to be achieved at a fast speed. In methods 2) and 3), controlling the parameters requires a drive power that is larger than 10 W; however, a digital data signal exhibits a low power level. However, method 4) comprises plenty of ASK products, which exhibit a fast response time and a low data signal power level. Fig. 3 depicts the characteristic changes in the output power of the injection-locked magnetrons with the injection power. The maximum shifts in the output power of the 2.45- and 5.8-GHz

TABLE I
Parameters and Conditions of the Injection-Locked Magnetron Experiments

Band	5.8 GHz	2.45 GHz
Maker	Panasonic	Panasonic
Type	M5801J	2M236M42
Anode Current	250 mA	140 mA
Anode Voltage	4.48 kV (DC)	3.65 kV (DC)
HVPS mode	CC	CC
Filament Voltage	3.35 V (AC)	OFF
Filament Current	7.4 A	OFF
Output Frequency	5.774 GHz	2.445 GHz
Output Power	614 W	309 W

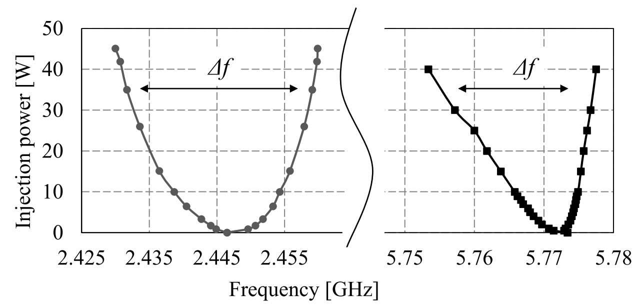

Fig. 2. Characteristics of the locked frequency range of the 2.45- and 5.8-GHz band magnetrons versus the injection power.

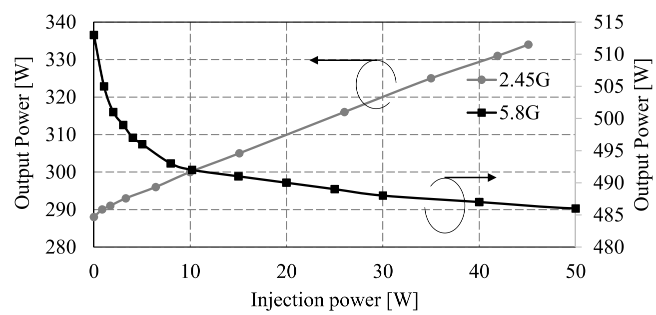

Fig. 3. Changes in the output power of the magnetrons with the injection power levels.

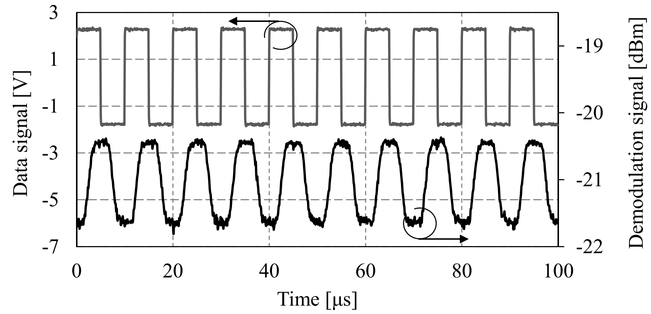

Fig. 4. Result of the data signal and demodulation signal using a 5.8-GHz band injection-locked magnetron ASK system.

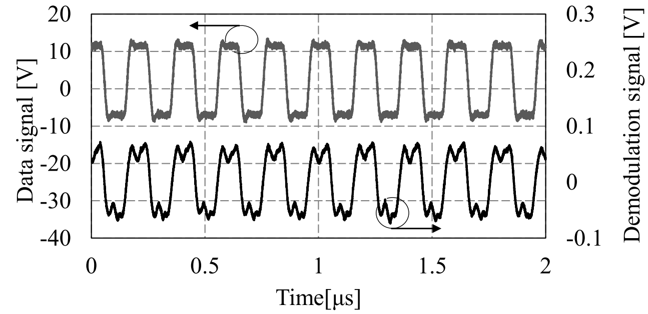

Fig. 5. Results of the PSK data signal and the demodulating signal.

band magnetrons were 40 W (−9.16 dB, 12.1%) and 30 W (−12.5 dB, 5.56%), respectively. Therefore, an injection-locked magnetron ASK system was developed by adjusting the injection power level.

A 5.8-GHz injection-locked magnetron modulation system was developed and assessed. As illustrated in Fig. 1, the carrier signal was set to be a 5.774-GHz sine signal that was generated from signal generator 1. A 100-kHz (200 b/s, 1 Hz = 2 symbol rate) square wave was provided as input to signal generator 1 as the external data signal. Signal generator 1 modulated the data signal on the carrier signal through ASK, and the amplitude modulation depth was set to be 70%. Furthermore, the modulated signal went through a 50-dB power amplifier (R&K A252HP-R). The power of the injection signal that was injected into the 5.8-GHz magnetron via a circulator shifted from approximately 6.6–22 W. The magnetron output power was measured by a signal analyzer (Agilent N9010A VSA89601), and it was observed to shift by approximately 6%. Fig. 4 depicts the results of the demodulated signal. This injection-locked magnetron output a lower amplitude depth than the injection signal, which is different compared to an amplifier because the magnetron output exhibits a fluctuating gain with an increase in the injection power. The amplitude modulation depth of the injection power affects the magnetron output power shift level. The low part amplitude of the injection power should maintain the functionality of the magnetron in a frequency-locking state. A fast data rate requires a considerably extensive bandwidth; however, the bandwidth should be narrower than the locked frequency range Δf, as depicted in Fig. 2.

In this experiment ($P_o/P_i = 13.5$ dB), it was observed that the amplitude of magnetron output was shifted in the 60-Hz noise delivered by the ac power filament. The filament of the magnetron was turned OFF after the magnetron began working to stop the 60-Hz noise. It should be noted that turning OFF the filament current in the case of a 5.8-GHz magnetron reduces the output power and the signal-to-noise ratio, while it improves the signal-to-noise ratio in the case of a 2.45-GHz magnetron.

B. Injection-Locked Magnetron for PSK

Based on the injection method described in Section II, the magnetron output can follow the injection signal. This experiment was conducted by following a similar procedure to that followed the case of the ASK experiment. In Fig. 1, signal generator 1 generated a 5.774-GHz sine wave as the carrier signal. A 5-MHz square wave was input into signal generator 1 as the data signal and was modulated on the carrier signal, which shifted 180° phase. Furthermore, the modulating signal passed through a power amplifier (R&K A252HP-R) to increase the power to 14 W after which it was injected into the magnetron via a circulator. The magnetron output locked with the injection power to deliver a modulated signal to the dummy load. Next, signal generator 2 (Vaunix LSG-602) provided a 5.774-GHz signal as the output (i.e., the same value as that of the carrier frequency). It was compared to the magnetron output signal by a double balanced mixer (R&K MX370), where the IF port of the mixer provided the demodulated signal through a low-pass filter as the output. An oscilloscope (Tektronix MSO2024) was used to measure the demodulated signal (Fig. 5). The remaining experimental parameters are listed in Table I. The magnetron output signal was demodulated, and the data signal was achieved at 10 Mb/s.

The rise time t_{rise} of this injection-locked magnetron modulation system would limit the maximum data transmission frequency f_p as according to the following relation:

$$f_p = \frac{\alpha}{t_{\text{rise}}}$$

where α is a constant (usually set to less than 0.35). The results of the experiment showed that the rise time t_{rise}, of this PSK system, which contained the phase shifter, the amplifier, and the magnetron, was 59 ns, the maximum data transmission frequency f_p was approximately 5.9 MHz, P_o/P_i was 16.42 dB, and the maximum transmission speed was 11.8 Mb/s.

The response time of the magnetron was expressed in another study as $(Qe/2\pi f)(P_o/P_i)^{1/2}$, which was derived from the Alder equation [7], [9]. This expression depicts that a high injection power causes the response time of the magnetron to decrease, which can increase the transmission rate.

Furthermore, a 60-Hz phase noise was observed at the magnetron output phase, which can be controlled by the PCM system, as demonstrated in [8]. Furthermore, the system was operated under a condition that the magnetron should only work in the frequency-locked state. Therefore, if the magnetron is not in the locking state, the PSK system should adjust the injection power frequency so that it becomes close to the magnetron self-oscillation frequency.

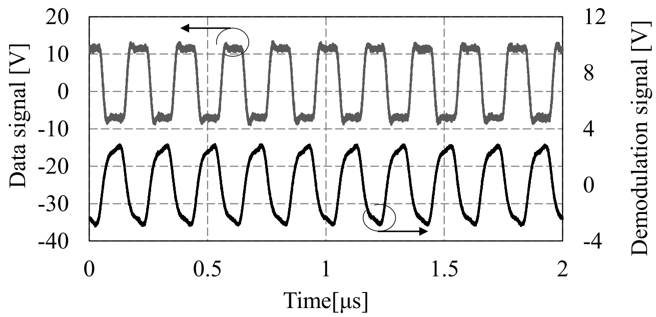

Fig. 6. Results of the FSK data signal and the demodulating signal.

C. Injection-Locked Magnetron for FSK

It is also possible to modulate a magnetron by FSK in a manner similar to the PSK modulation. FSK modulation offers several advantages such as strong noise immunity and low cost. Therefore, a similar experiment with identical experimental conditions (Table I) was conducted for FSK modulation. After the first step (input data) was performed, the carrier frequencies were set to be 5.774 and 5.776 GHz (deviation frequency: 2 MHz). Moreover, the FSK signal was amplified to 14 W and injected via a circulator into the magnetron. The magnetron was locked with the FSK signal, and the FSK signal was amplified and delivered to the dummy load. Furthermore, a frequency demodulator (Pakite PAT-630) demodulated the magnetron output signal. Finally, the oscilloscope measured the demodulated signal (Fig. 6). This injection-locked magnetron modulation system can amplify the FSK signal to 10 Mb/s.

The bandwidth of the injection-locked magnetron system for FSK should be smaller than the locked frequency range Δf. In addition, a small value of modulation index (quotient of the deviation frequency to the data rate) results in the production of less sidebands. Furthermore, multiple FSK modulations can improve the bandwidth efficiency. Therefore, over a constantly locked frequency range or a constant bandwidth, a small value of the modulation index and multiple FSK modulations can result in a fast transmission rate.

IV. Discussion of the Modulation Performance

The injection-locked magnetron acted as an amplifier for the modulation system. However, there are some differences between the injection-locked magnetron and the amplifier. The gain of an amplifier constantly increases with the input power, while the magnetron exhibits a fluctuating gain, as depicted in Fig. 3. Thus, the magnetron exhibits a lower gain with a considerably wide locked range. The injection power affects the frequency and phase of the magnetron when it works in an injection-locked state. Therefore, the magnetron output phase and frequency could follow the injection signal.

Both periodic and aperiodic signals were detected because the data signals exhibited a considerable difference between their magnetron modulation performances. Fig. 7 depicts the spectral curve of the injection-locked magnetron for the FSK modulation system output versus the periodic and aperiodic data signals. As illustrated, periodic signals do not accurately

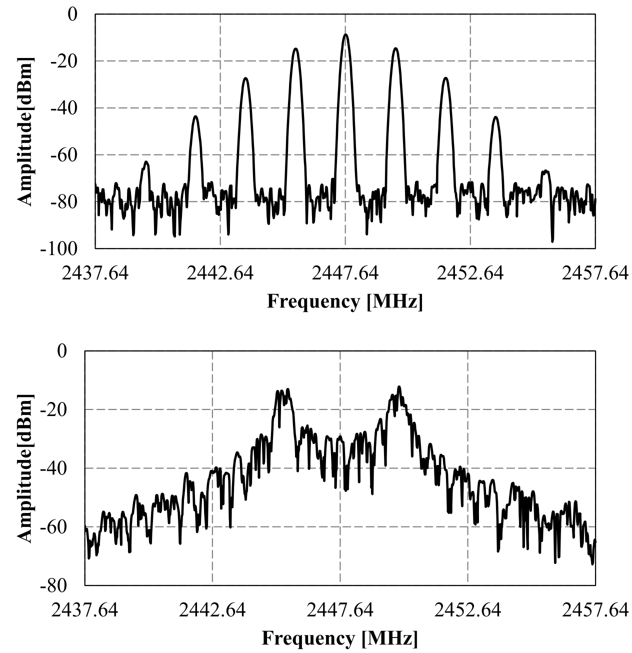

Fig. 7. Spectral curve of the injection-locked magnetron FSK system with different data signals (data signal on the upper trace: a square wave and lower trace: PN9 code).

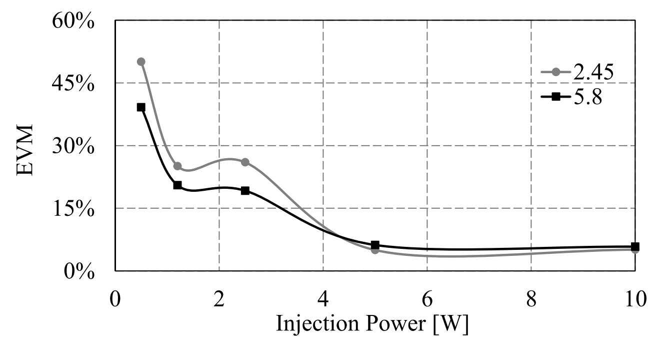

Fig. 8. Changes in the EVM of the injection-locked magnetron system for PSK with the injection power levels.

reflect the locked frequency range or the data error level. In the experiment, a pseudo noise (PN) sequence (PN 9: $2^9 - 1 = 511$ bit) was modulated on the carrier signal by a digital signal generator (Agilent E4432B), while a signal analyzer (Agilent N9010A VSA89601) was used to analyze the error vector magnitude (EVM) of the modulating signal. EVM compares the measured locations with the ideal locations. Therefore, it helps to evaluate the quality of the magnetron digital modulation. The remaining relevant operating parameters are presented in Table II.

Fig. 8 depicts that the 2.45- and 5.8-GHz band magnetrons exhibit similar EVM results at the PSK modulation of 2 Mb/s. A signal modulation can be achieved when the injection power is larger than 5 W. Therefore, the 5-W injection power level was set as the condition for the magnetron to work under the injection-locked state at a transmission bandwidth at 2 Mb/s. The injection power is further increased under these conditions; however, the EVM value remains unchanged. Furthermore, the transmission rate was changed from 0.5 to

TABLE II
PARAMETERS OF THE INJECTION-LOCKED MAGNETRON EXPERIMENTS

		Injection signal (Signal generator & Amplifier)				Magnetron output			
Type	Data rate	EVM	Mag Err	Phase Err (deg)	Freq Err (Hz)	EVM	Mag Err	Phase Err (deg)	Freq Err (Hz)
ASK	200 kbps	1.74%	1.48%	0.5404	3489.5	2.29%	0.49%	1.3074	3708.7
BPSK	10 Mbps	4.24%	4.02%	0.7763	78.137	8.85%	8.33%	1.7048	3397.1
QPSK	10 Mbps	5.29%	4.10%	1.9337	3.6068	9.21%	7.17%	3.2776	−18.842
8PSK	5 Mbps	5.62%	4.06%	2.2542	41.388	11.37%	6.36%	5.4577	78.593
MSK	10 Mbps	3.03%	0.91%	3.6525	3.3269	6.56%	3.02%	2.8858	30.079
Type	Data rate	FSK Err	Mag Err	Carr Offset (kHz)	Deviation (Hz)	FSK Err	Mag Err	Carr Offset (kHz)	Deviation (Hz)
2 FSK	10 Mbps	2.61%	0.83%	1.7313	975.96	6.38%	8.12%	0.1730	928.88
4 FSK	10 Mbps	2.22%	0.75%	−2.4116	972.16	5.13%	0.64%	2.9138	929.53
8 FSK	5 Mbps	0.78%	0.78%	0.17517	993.53	1.45%	0.62%	0.2636	981.90
16 FSK	10 Mbps	2.09%	0.65%	0.66101	976.22	4.20%	0.61%	10.662	1025.4

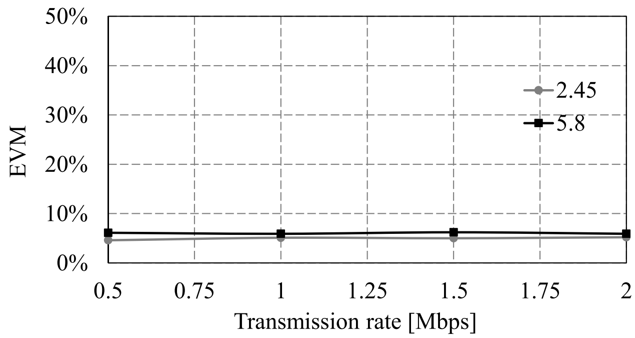

Fig. 9. Changes in the EVM of the injection-locked magnetron system for PSK with the transmission rates.

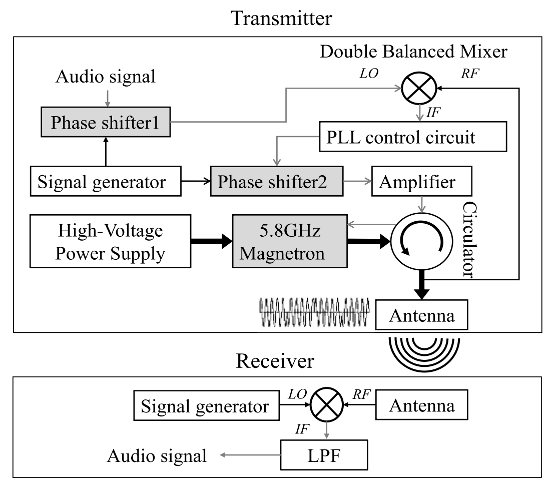

Fig. 10. Schematic of the PM injection-locked magnetron system.

2 Mb/s, while the injection power was fixed at 5 W. It was observed that the 2.45- and 5.8-GHz band magnetrons exhibited similar performances (Fig. 9). Consequently, it can be concluded that, under injection-locked conditions, adjusting the transmission rate does not affect the transmission quality. Therefore, in a case where the injection power is high enough to constantly lock the magnetron, the speed of modulation will be limited by the response time of the injection-locked magnetron.

Furthermore, while conducting the ASK, multivalue PSK, and multivalue FSK modulations, a PN9 data signal was used to evaluate the quality of the modulating signal. In addition, a 2.45-GHz band magnetron was used to perform the measurements. To determine the modulation limit of the magnetron, the maximum gain under the injection-locked conditions was set. The magnetron output power was 309 W (P_o/P_i: 13.43 dB) at an injection power of 14 W. Furthermore, the PN9 data signal of the modulating signal having a speed of 10 Mb/s was tested, as depicted in Table II. (It was 5 Mb/s for both eight PSK and eight FSK.) It was also observed that the magnetron increased the error rate in all the modulation methods. However, under identical conditions, the communication quality of the FSK modulation was observed to be better than that of the PSK modulation, which can be attributed to the higher antinoise ability of the FSK modulation. In the vector signal analyzer (VSA 89601) software, the filter was set as root raised cosine and the Alpha/BT value was 0.35. The EVM and FSK error was measured when it changed less than ±1%; values of them lower than 10% can be considered as valid data transmissions.

V. DEMONSTRATION EXPERIMENTS

A. Demonstration of a Phase-Controlled Magnetron for Transmitting an Audio Signal

A PCM phase modulation (PM) system (Fig. 10) was used to demonstrate an audio signal transfer. An audio of Hello was input into phase shifter 1 that demodulated it. The magnetron output phase was further compared with the phase of the modulating signal in the mixer. The phase difference signal was input into the phase-locked loop (PLL) circuit to control phase shifter 2, which changed the phase of the signal injected into the magnetron. Using the PLL circuit, the phase difference was gradually converged to zero, and the magnetron output followed the modulating signal. The receiver antenna was compared with the signal generator which worked at the same frequency as that of the transmitter, and the mixer outputted the phase difference. Fig. 11 depicts a part of an audio signal from among which high-frequency noise that is out of the human hearing range (i.e., 20 Hz–20 kHz) is observed to be

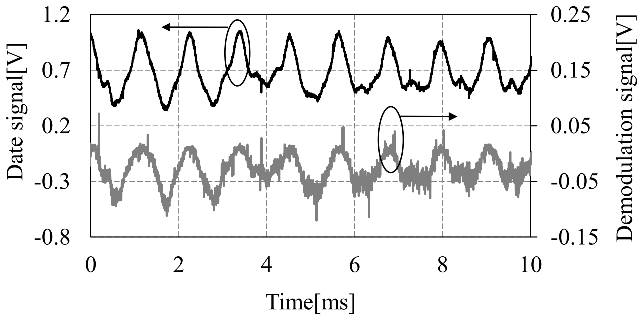

Fig. 11. Waveform of the PM injection-locked magnetron.

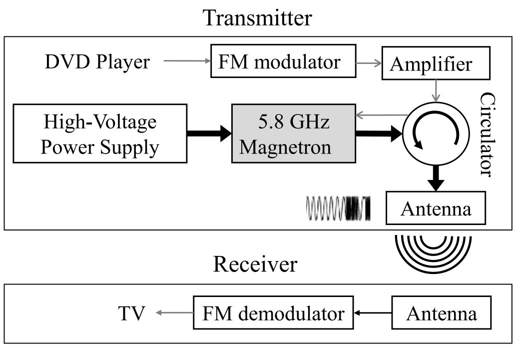

Fig. 12. Schematic of the FM injection-locked magnetron system.

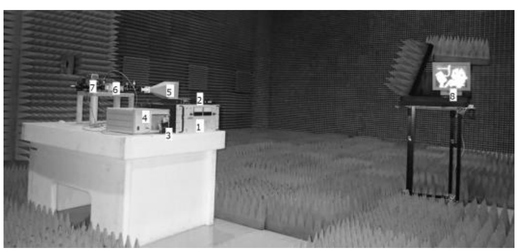

Fig. 13. Photograph of the FM injection-locked magnetron system (1: high-voltage power supply; 2: DVD player; 3: FM modulator; 4: amplifier; 5: horn antenna; 6: circulator; 7: magnetron; and 8: TV).

present in the demodulated signal. The rise time t_{rise} of this PM system was observed to be 1.78 μs. In addition, it was observed that this system can avoid the 60-Hz phase noise from the filament or the environmental impact and can amplify the multivalue PSK signal. Therefore, the analog PM system acted as a radio broadcast.

B. Demonstration of an Injection-Locked Magnetron for Transmitting a Video Signal

Similarly, the transmission and demodulation of a video signal were demonstrated by an analog frequency modulation (FM). In this case, an injection-locked magnetron FM system was designed (Figs. 12 and 13). The cores of the FM modulator and demodulator (Pakite PAT630) are IC RTC6705 and RTC6709, respectively. The FM modulator generated a 5.8-GHz band FM signal modulated with a video signal and two modulated audio subcarriers at 6 and 6.5 MHz, respectively. A DVD player outputted the signal to the FM modulator, and the modulating signal was amplified to 10 W and injected into the magnetron. In the receiver, the demodulator demodulated the video and audio signals and delivered them to the TV. Thus, the DVD signal was played on the TV. It should be noted that the long distance in this system was simulated using a microwave absorber. Therefore, it can be concluded that the analog FM system acted as a TV broadcast.

VI. Conclusion

In this paper, several modulation methods were assessed using injection-locked magnetrons, which behaved like a narrow bandwidth amplifier. The 5.8-GHz injection-locked magnetron (P_o/P_i: 13.5 dB) transmitted the modulating signal at a rate of 200 kb/s in the ASK experiment. The data transmission in the PSK and FSK (P_o/P_i: 16.42 dB) experiments achieved a high speed of 10 Mb/s. The 2.45-GHz injection-locked magnetron (P_o/P_i: 13.43 dB) was assessed using ASK, multivalue PSK, and multivalue FSK performances. The EVM in these cases were observed to be less than 10% at a data rate of 10 Mb/s.

When the magnetron worked in a frequency-locked state, the injection power level was observed to have no effect on the quality of the modulating signal. Increasing the injection power level was observed to produce an extensive frequency range, a high response time and a fast data transmission rate.

In addition, as a demonstration of system viability, an audio signal was successfully transmitted by the PCM PM system and demodulated; furthermore, a video signal was also transmitted by the injection-locked magnetron FM system and demodulated.

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