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Experimental Study of Microwave Pulse Compression Using a Five-Fold Helically Corrugated Waveguide

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***Abstract*—This paper presents the experimental study of microwave pulse compression using a five-fold helically corrugated waveguide. In the experiment, the maximum power compression ratio of 25.2 was achieved by compressing an input microwave pulse of 80-ns duration and 9.65–9.05-GHz frequency swept range into a 1.6-ns Gaussian-envelope pulse. For an average input power of 5.8 kW generated by a conventional traveling-wave tube, a peak pulse output power of 144.8 kW was measured corresponding to an energy efficiency of 66.3%.**

***Index Terms*—Helically corrugated waveguides (HCWs), microwave pulse compression, mode coupling.**

I. INTRODUCTION

PULSE compression technology that converts long-duration low-power pulses into short high peak-power pulses is commonly used in applications that require high peak power and pulsed operation, such as sonar and radar systems [1], [2]. Pulse compression can be used to improve the space and time resolution, as well as the signal-to-noise ratio of radar systems [3] and image brightness in multiphoton imaging systems [4]. It can also be used to generate intense ultra-short laser pulses for studying physical phenomena in short time scales [5]–[7].

By compressing a multi-megawatt-long duration pulse with an appropriate compression ratio, it is possible to generate gigawatt-level microwave radiation, which is otherwise extremely difficult to realize. Gigawatt-level microwave radiation can be achieved by a frequency-swept multi-megawatt pulse generated by a high power vacuum electronic device acting as the input source for a microwave pulse compressor based on a high-fold helically corrugated waveguide (HCW) [8].

The use of a metal waveguide as a dispersive medium to generate high peak-power microwaves was proposed [9]. The principle is to use a swept frequency modulated pulse train with a monotonically increasing group velocity propagating through the waveguide. The tail of the pulse will overtake its leading edge, which results in pulse shortening and growth in power amplitude if the losses are small. The maximum compression ratio happens at the exit of the waveguide where all the frequency components arrive at the same time. The compression ratio is calculated from the electromagnetic wave propagation along an isotropic dispersive medium and is given by

$$K = \Delta f L\left(\frac{1}{V_{g1}} - \frac{1}{V_{g2}}\right)e^{-\gamma L} \tag{1}$$

where V_{g1} and V_{g2} are the group velocities of the beginning and the end frequencies of the microwave pulse. To achieve a high compression ratio K, the dispersive media requires operation over a wide frequency band to give a large Δf with a large monotonic group velocity difference in the operating frequency band, which allows a large $(1/V_{g1} - 1/V_{g2})$ value. This provides the capability of supporting a long pulse width in a medium of specific length L, as well as a low equivalent loss factor γ [9].

A smooth waveguide can also have a relatively large monotonic group velocity difference over a wide frequency range. From the dispersion curve of the smooth waveguide, the group velocity has a large change near the cutoff frequency (shown as ω_1 and ω_2 in Fig. 1) and the group velocity changes less at the frequencies further away from the cutoff frequency. Therefore, most of the frequency range suitable for the pulse compression is near the cutoff. However, the large ohmic loss close to cutoff prevents a high compression ratio being achieved resulting in low energy efficiency as evidenced by a compression ratio of 7 measured in an experiment using a 19.2-mm-diameter smooth 6.6-m-long circular waveguide at X-band [9]. The new HCW studied in this paper demonstrates much better performance than the smooth waveguide. The cross-sectional and longitudinal periodicities of an HCW allow new operating eigen modes (W_1 and W_2) to exist by resonant coupling of modes 1 and 2 in the circular waveguide, as shown in Fig. 1. Around the coupling point P_0, the group velocity of operating mode W_1 is monotonically decreasing over a relatively wide frequency band as frequency increases. W_1 also has a low ohmic loss at this frequency band as it is far from its cutoff. A further advantage of the HCW is that because the rapid change in group ve-

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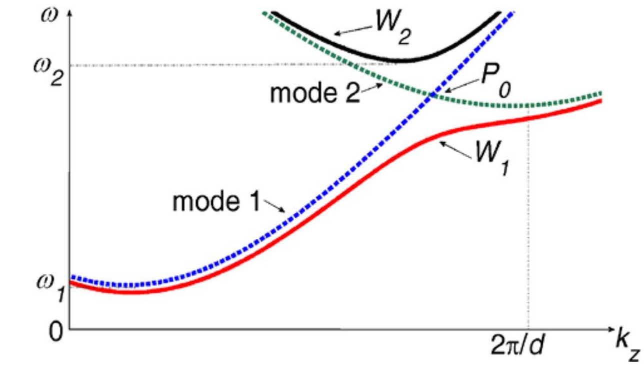

Fig. 1. Mode coupling in the HCW. The eigenmodes W_1 and W_2 are the result of the coupling of modes 1 and 2 in the circular waveguide. The group velocity of operating mode W_1 is monotonically decreasing over a relatively wide frequency band as frequency increases around the coupling point (P_0).

locity is achieved using an inflexion in the dispersion curve, an amplifier can be used as the input source. On the other hand, if the compressor operates at near cutoff frequency, then a big reflection could occur due to a small difference in the waveguide diameter as a consequence of the tolerance achieved during machining. The reflection may cause feedback oscillations and possible damage to the amplifier. The use of the HCW can mitigate such risks.

The HCW has attracted significant interest and has been successfully used in the gyrotron traveling-wave amplifier (gyro-TWA) [10], [11], and gyrotron backward-wave oscillator (gyro-BWO) [12]–[14] to improve the beam–wave interaction bandwidth in both types of devices. The first pulse compression experiment using the HCW was carried out on a three-fold structure. The spatial harmonic TE_{11} mode in the circular waveguide was chosen to couple with the TE_{21} mode to generate the operating mode. Using these two low-order modes, the optimum frequency sweep signal was investigated and a compression factor of 25 in the peak power was obtained [15]. An 80-ns microwave pulse with an average power of 5.6 kW and a 5% frequency sweep in X-band was compressed into a Gaussian-shaped waveform with a 1.5-ns full width at half maximum (FWHM) with a peak power of 140 kW. The maximum power-handling capability of this 29.4-mm mean diameter three-fold HCW can be calculated from the maximum field inside the HCW and the continuous microwave breakdown field. The power-handling capacity of the three-fold HCW in air was calculated to be about 30 MW. Although in pulse operating mode the breakdown field can be much higher than in continuous mode operation, about 1 MV/cm for 10-ns pulse duration [16], [17], it is still difficult to handle gigawatt-level microwave pulses as the power-handling capability is heavily dictated by the waveguide diameter. In this paper, the pulse compression experiment using a five-fold HCW with a larger average diameter of 65.7 mm for enhanced power handling is presented. The dispersion of and preliminary compression experiments based on the five-fold HCW have been briefly reported in [18]. In this paper, the optimized experimental results are presented with comparisons to new simulation results from the microwave pulse compressor. Also, to give the readers a full picture of the experiment, the power-handling capability and the construction of the five-fold HCW are presented in this paper with an expanded theory of the pulse compression.

This paper is organized as follows. Section II describes the design of the waveguide components for microwave compression. Section III presents the construction and measurement of the waveguide components. In Section IV, the experimental and simulation results on the pulse compression are reported and discussed. Section V presents the conclusion.

II. Design of the Waveguide Components for Microwave Compression

The HCW was designed to have a mean waveguide diameter at least twice that of the three-fold one while operating in the same frequency range. High-order-mode operation was therefore required and it was possible to achieve this by the coupling of the spatial harmonic TE_{31} mode with the TE_{22} mode, which determined a fold number of 5 for the HCW from the azimuthal synchronism condition $m_2 - m_1 = m_B$ to be satisfied, where m_1 and m_2 are the azimuthal indices of the two coupling modes and m_B is the azimuthal period of the waveguide. $m_2 = 2$ and $m_1 = -3$ indicates an opposite rotation of the TE_{31} mode [19]. The dispersion characteristic can be changed by varying the HCW's geometry whose profile is governed by the expression $r(\theta, z) = R_0 + R_1 \cos(5\theta + 2\pi z/d)$ in a cylindrical coordinate system (r, θ, z). The mean radius R_0 mainly decides the operating frequency range; the corrugated depth R_1 mostly controls the coupling strength, and the period d directly affects the position of the coupling point. The design of the HCW for pulse compression requires accurate prediction of the dispersion curve as the group velocity is defined as $d\omega/dk_z$.

A small change in the dispersion relation will cause a large difference when calculating the group velocity, especially when the HCW operates in the small k_z range. Different methods have been developed to calculate the dispersion curve with different accuracies and computing times, including the 1-D analytical method [19], [20], the specialized 2-D finite-element method (FEM) [21], and the full 3-D finite-difference time-domain method (FDTD), or the FEM [22]. The 1-D analytical method is based on the method of perturbation. It is the fastest method and is useful for preliminary design and setting the parameter range of the compressor, but is not accurate at large corrugation depths. The 3-D FEM simulation typically takes 4 h on a PC with a four-core processor at 2.8 GHz and 16-GB memory to simulate one period of the five-fold HCW. It is not suitable for optimizing the parameters, however, it is able to provide the dynamic field information inside the waveguide. The 2-D simulation based on a helicoidal coordinate transform provides a good balance between the accuracy and the computing time (5 min using the same hardware as compared to the 3-D case), although it is more complicated to develop the in-house code to implement an FEM solver with a helicoidal coordinate. The optimal dimensions used in the experiments were derived to be a five-fold HCW with $R_0 = 32.84$ mm, $R_1 = 2.43$ mm, and $d = 33.26$ mm. The total length of 2.86 m was decided by the optimum tradeoff between the compression ratio and the energy efficiency. The simulated dispersion curves by the different methods and the experimental measurement were shown in [18].

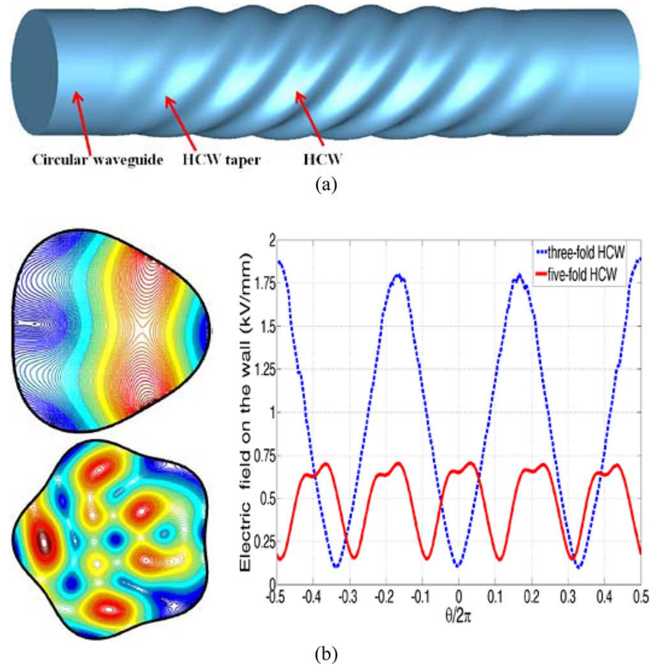

Fig. 2. (a) Simulation model in the CST Microwave Studio. (b) Electric field and the electric field on the wall of the three- and five-fold HCW at 9.6 GHz.

The 3-D FDTD simulation code CST Microwave Studio was used to study the dynamic electric and magnetic fields inside the HCW. In the simulation, the HCW was connected with a HCW taper whose corrugation is linearly reduced to zero and then followed by a circular waveguide, as shown in Fig. 2(a). A circularly polarized TE_{11} mode was stimulated at the input port for the three-fold HCW simulations and TE_{31} mode for the five-fold HCW to produce the desired operating eigenmodes. From the simulations, the maximum electric field inside the five-fold HCW was 0.7 kV/mm at 1-MW input power, which is 37.4% of the maximum electric field in the three-fold HCW. The maximum power capability of the five-fold HCW is about seven times higher as compared with the three-fold one operating in the same frequency range. Fig. 2(b) shows the contour plot of the electric fields at the cross section of the three- and five-fold HCWs, as well as the electric field strength at the wall of the three- and five-fold HCWs.

Compared with exciting the fundamental circularly polarized TE_{11} mode in the three-fold HCW, it is more complicated to excite the circularly polarized TE_{31} mode in the five-fold HCW. A mode convertor was therefore designed to transfer the input TE_{11} mode into the TE_{31} mode with sufficiently high mode conversion purity as well as low TE_{11} reflection at the operating frequency band. The principle of operation is based on mode-selection Bragg scattering by a waveguide with a periodic corrugation. The mode convertor requires a high coupling coefficient between the incident and the output waves, which can be analytically calculated from the coupled mode theory based on the perturbation method. From the azimuthal synchronism condition, a fold number of 4 is required. The period of the mode convertor will satisfy the axial synchronism condition $2\pi/d = h_1 - h_2$, where h_1 and h_2 are the axial wavenumbers of the TE_{11} mode and the spatial harmonic of the TE_{31} mode

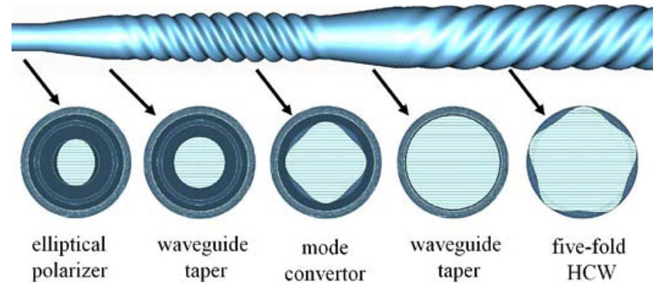

Fig. 3. Connection and cross-sectional shape of the waveguide structures.

[23], [24]. The geometry was refined and verified by using the 3-D FDTD code CST Microwave Studio after the preliminary theoretical analysis. More than 95% of the power of the TE_{11} mode was converted into the TE_{31} mode in the frequency range of 8.9–9.9 GHz and the reflection coefficient of the TE_{11} mode is less than -30 dB. The five-fold HCW and the mode convertor both contain tapering sections, which linearly reduce the corrugated depth to zero, thereby converting from helical geometries into circular shapes to ensure the TE_{31} wave is smoothly converted to the operating eigenwave. The four-fold mode convertor requires a circular polarized TE_{11} wave as the input, therefore an elliptical polarizer was designed and constructed that was able to convert the polarization of the TE_{11} wave between linear polarization and circular polarization [25]. The center frequency was set at 9.3 GHz and it was able to achieve more than 98% energy conversion from one polarization to the other in a frequency band of over 10%. Four circular waveguide tapers (two at each side of the compressor) were used to match the different radii between the waveguide components as well as to cut off the undesired reflection for maintaining mode purity inside the waveguide. The connection of the waveguide structure and the cross-section view of each component are shown in Fig. 3. At the other end of the five-fold HCW, the same configuration was used.

III. Construction and Measurement of the Waveguide Components

The five-fold HCW and four-fold mode convertor were constructed separately. The inner surface of the HCW and the mode convertors were machined using facilities at Strathclyde University, Glasgow, U.K., to manufacture positive aluminum mandrels using a four-axis computer numerical control (CNC) machine with the copper grown on the aluminum by electroforming with a thickness of 6 mm. Finally, the aluminum was chemically dissolved to leave the copper waveguides. The machined aluminum formers and the final copper waveguides are shown in Fig. 4. The waveguides were then carefully joined and tightened together. Care was taken to match the cross sections of the five-fold HCW pieces because of their irregular shape and to ensure the system was well aligned.

The mode convertor, elliptical polarizer, and waveguide tapers are also dispersive. Although they are relatively short compared with the five-fold HCW, they will still contribute to the whole dispersion curve and affect the optimal frequency sweep. In the 3-D FDTD simulation, the compression ratio drops from

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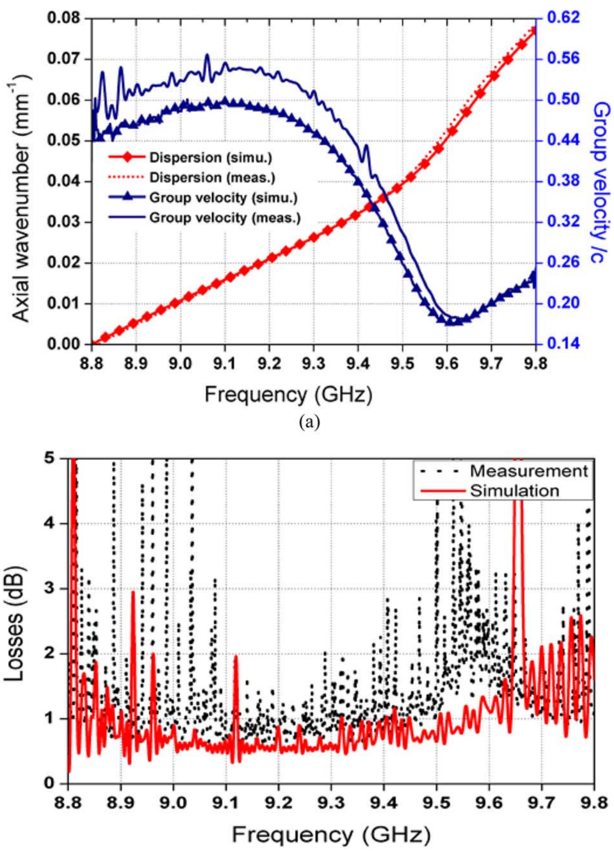
(a) (b)

Fig. 4. (a) Machined aluminum formers. (b) Final copper waveguides.

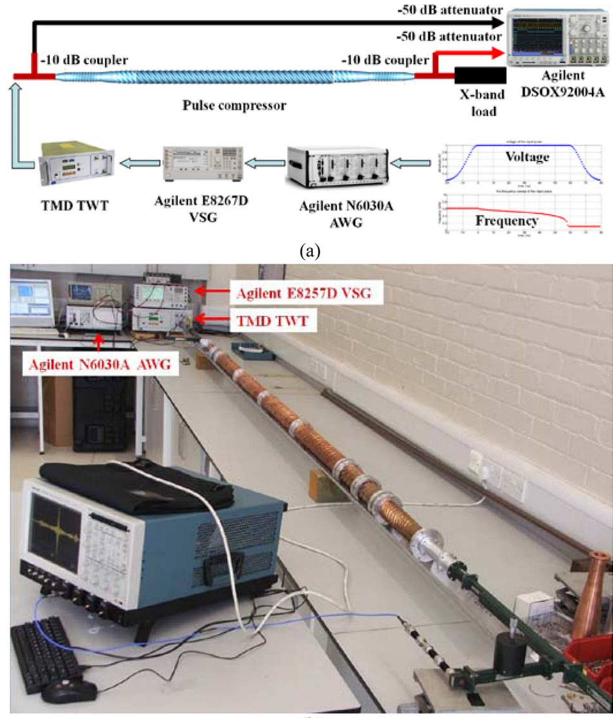


(a)

(b)

Fig. 5. Simulated and measured: (a) dispersion characteristics and group velocity and (b) losses of the pulse compressor.

22 to 9 if the dispersion of the other components besides the five-fold HCW is not taken into account. Therefore, the dispersion characteristics of the whole waveguide structure that includes all the waveguide components was measured using an Anritsu 37397A vector network analyzer (VNA). The simulated and measured dispersion characteristics, group velocity, and the losses are shown in Fig. 5. The difference of the dispersion curve between the simulation and measurement is mainly caused by the machining tolerance of the waveguide components and the imperfect alignment of the waveguides. The sharp spikes in the measurement and simulation losses are due to small cavity effects of the elliptical polarizers and the mode convertors. The relatively large loss at the spike frequencies will result in smaller field amplitude at these frequencies. From (1), the losses will result in the reduction of the compression factor as



(a)

(b)

Fig. 6. (a) Schematic and (b) photograph of the microwave pulse compression experimental setup.

well as the energy efficiency. From the group velocity, the frequency band that can be used for compressing the microwave pulse was 9.05–9.65 GHz.

IV. Pulse Compression Experimental Results

An input pulse in rectangular shape was used in the experiment. Its frequency components were calculated from the measured dispersion curve of the whole device. The starting frequency was 9.6 GHz, which corresponds to the minimum group velocity (about 0.15 c, where c is the speed of light) in the compressor. The ending frequency was 9.1 GHz, which has the maximum group velocity (about 0.5 c). The inverse of the group velocities of the frequency components are a linearly decreasing function of the entrance time of the input pulse. The duration of the flat part of the input pulse was 63.8 ns, and both the rise and fall time of the pulse were 20 ns. To generate the 0.6-GHz bandwidth frequency sweeping signal as the input, an arbitrary waveform generator (AWG) (model: Agilent N6030A) which is capable to generate a ±500-MHz modulated signal was chosen and programmed. The ±300-MHz frequency sweeping signal was then mixed with a 9.3-GHz oscillation signal by a vector signal generator (VSG) (model: Agilent E8257D) to generate the frequency sweeping signal at the frequency range from 9.65 to 9.05 GHz for pulse compression. To demonstrate the experiment at a multiple kilowatts power level, a conventional X-band traveling-wave tube (TWT) from TMD Ltd. was used to amplify the low-power input signal to a few kilowatts. The high-power voltage signals from the TWT and the output compressed pulses was recorded by a 20-GHz digitizing storage oscilloscope (DSO) (model: Agilent DSOX92004A), which was protected with the use of a −10-dB coupler with additional

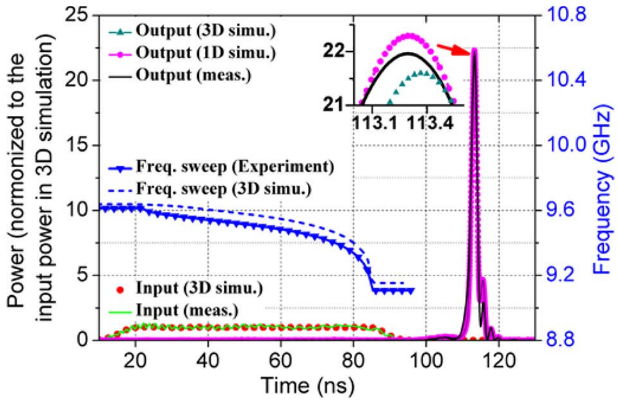


Fig. 7. Simulated and measured compressed pulses. The detail of the compression factors for the different cases are shown in the inset.

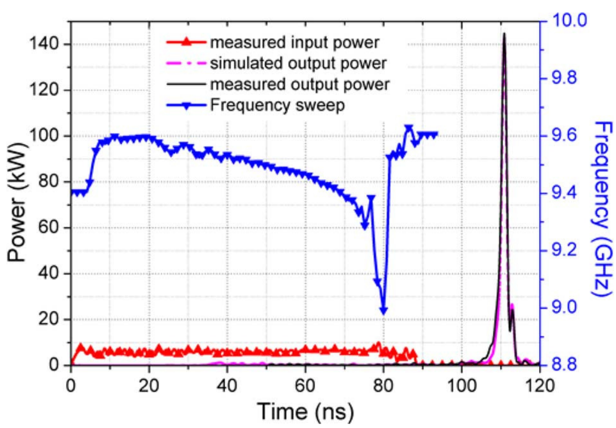


Fig. 8. Measured and simulated microwave outputs from the compression experiment and input microwave waveform and frequency sweep.

−50-dB attenuation. The setup of the pulse compression experiment is shown in Fig. 6.

The compressed output voltage signals can be calculated quickly using the 1-D analytical simulation in which the microwave pulse propagation process in the compressor can be approximated as a plane wave moving forward along an isotropic dispersive medium, and the dispersive medium has an equivalent dispersion characteristic of the whole waveguide system. The 3-D FDTD simulation was also used to study the field evolution during the compression process. The output voltage signals from the 1-D analytical simulation, 3-D FDTD simulation, and the experimental measurement were analyzed to obtain the compression ratio. The experimental voltage signals were transformed into the complex values to get the phase information, as well as the imaginary part of the signal by using the inverse Fourier transform. The power of the signals was then calculated from the complex values. The power compression factors for the three cases are 22.2, 21.5, and 21.9, respectively, and agree well with each other. The input signal and the compressed output signal are shown as Fig. 7. About 61.5% of the input energy was compressed into the main body of the output pulse and the pulse width was 1.9 ns (here it assumes the main body of the output pulse is a Gaussian-like waveform with a 1.9-ns FWHM).

By further adjustments on the frequency sweeping signal, like changing the frequency on the rising and falling edges of the pulse in the optimum frequency swept signal, or increasing the pulse duration, which means larger input energy, it was possible to achieve an even higher compression factor. For example, the best compression factor of 25.2 was obtained using a frequency sweeping signal with an 80-ns flat part in the pulse, with an average power of the input pulse of about 5.80 kW, which resulted in a peak power of the compressed pulse of 144.8 kW with a pulse width of 1.6 ns, as shown in Fig. 8. For this compression ratio of 25.2, the energy conversion efficiency was measured to be 66.3%.

V. Conclusion

The paper has presented the operating principle, the design, and the experimental study of microwave pulse compression. To achieve a high power-handling capability, a five-fold HCW that operates at a higher order mode was employed. The dimensions of the HCW were initially studied using a 1-D analytical method based on the perturbation theory. They were further optimized by using the 2-D FEM based on the helicoidal coordinate transform, and the dispersion curve was verified by the 3-D FDTD code CST Microwave Studio and measurement of the dispersion using a VNA. A compression ratio of 25.2 was achieved by compressing an input microwave pulse of 80-ns duration and 9.65–9.05-GHz frequency swept range into a 1.6-ns Gaussian-envelope pulse. As a result, a seven times greater power-handling capability was achieved as compared to the lower mode pulse compressor. The five-fold HCW provides a promising way to generate gigawatt-level microwave radiation by compressing multi-GW-level frequency-swept output power from relativistic backward wave oscillators. It advances the field of ultra-high-power microwave pulse generation, which has a wide range of beneficiaries ranging from security screening to materials testing.

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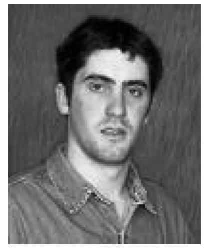

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