High Power Microwave Pulse Compression Using a Helical Slow-Wave Structure

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Abstract. One interesting method of microwave pulse compression is passive–frequency-based microwave pulse compression where a dispersive medium is used to compress a frequency swept pulse. Oversized circular waveguide having helical corrugation supports eigenmodes that are suitable for pulse compression for frequency modulated input pulse as shown by Brat et.al. [IEEE Trans. Plasma Sci., vol. 33, no.2, pp. 661–667, 2005.]. In this paper, theoretical studies on microwave pulse compression in helically corrugated waveguide is presented. The numerical results show a eleven fold peak power compression.

1. Introduction
Ultra high power short microwave pulses have been produced in recent years due to its wide range of applications [1]. These high power pulses can be produced by microwave pulse compression. One of the common methods to achieve necessary power levels is to use electron beam–wave interaction to amplify the microwave pulse to higher powers. To further increase the peak output power, an economically viable method is to compress a long duration lower power pulse into short duration higher power pulse. The principles and method of pulse compression vary depending on their application [2].

Compression of smoothly frequency modulated electromagnetic pulses in dispersive medium is well known and actively used in microwave electronics and laser physics. Hollow metal waveguides representing dispersive media are attractive for the microwave pulse compression because of their capabilities of handling very high power, relative compactness and simplicity. In a dispersive medium, the group velocity of any wave propagating through it is dependent on the frequency of the wave. Therefore, if a microwave pulse is produced in which the wave is swept from a frequency with a low-group velocity to a frequency with a high-group velocity, the tail of the pulse will move to overtake the front of the pulse, resulting in pulse shortening and a corresponding growth in amplitude if the losses are sufficiently small. If a cylindrical waveguide is used as the dispersive medium, the optimum region of operation is where the largest change in-group velocity with frequency occurs, which is near cut-off for a smooth waveguide.

One of the solutions is to use a helically corrugated waveguide, which was previously studied intensively for use as an interaction region for a gyro-TWA [3]. The helical wall perturbation can provide selective coupling between a higher and a lower circularly polarized mode avoiding the Bragg reflection zones, which would inevitably appear in the case of an axisymmetric corrugation because of
coupling between forward and backward propagating spatial harmonics. This coupling results in an eigenmode where the dispersion characteristics of one mode gradually transform into the other. If the parameters of the corrugation are chosen correctly, this can give the eigenwave a group velocity that decreases with frequency, and avoids regions with zero or negative group velocity, in its operating bandwidth, which is far from cut-off.

As the helically corrugated waveguide operates far from cutoff, the compressor provides much lower reflections at its input than the smooth circular waveguide. This allows the compressor to be used at the output of a high-power Cherenkov TWT. The second advantage is that the optimum frequency sweep in a helical compressor is from a high frequency to a lower frequency, and can be controlled by the corrugation parameters. This makes the helically corrugated waveguide compressor attractive for use at the output of a powerful relativistic BWO as this would require a beam voltage that decays with time for compression to take place [4].

This paper deals with the theoretical study to obtain a multigigawatt radiation power, which is based on passive compression of the microwave pulse compression generated in helically corrugated waveguide. Section 2 presents the general principles and relationships determining compression of frequency modulated pulses and considers the features of a dispersive medium in the form of a helically corrugated waveguide. Section 3 presents results and comparison to earlier experimental results.

2. Dispersion relation and pulse compression
In this section, the dispersion characteristics of the helically corrugated waveguides are presented. Considered a hollow metallic waveguide with inner wall radius \( R(z) = R_0 + h \cos(k_0 z + q_0 \theta) \). Here \( k_0 = 2\pi/l_0 \), \( l_0 \) being the periodicity in axial direction is while \( q_0 = 2\pi/q_0 \) is the periodicity in azimuthal direction and \( q_0 \) is the order of folds of helical corrugation.

In a periodically corrugated waveguide, the electromagnetic field can be represented as a superposition of the spatial harmonics. Using the boundary conditions that the tangential component of electric field must vanish on the helical boundary, we get a dispersion relation, to be published elsewhere, whose solution is:

![Figure 1](https://example.com/image)

**Figure. 1** Schematic view of a waveguide with a three-fold right-handed (q=3) helical corrugation.
Figure. 2 Dispersion diagram for three-fold helically corrugated waveguide: Mean radius \( R_0=1.47 \text{cm} \), corrugation period \( z_0=2.89 \), and amplitude \( h=0.19 \text{cm} \).

We assume that a quasi-monochromatic pulse at the input of the waveguide compressor. The shape of the pulse envelope is close to a Gaussian, which is given as

\[
u(z,t) = \frac{1}{2\sqrt{2\pi}} \int_{-\infty}^{\infty} A(\omega) \exp\left[i\left(k_z t - \omega t\right)\right] d\omega
\]

(1)

It is easy to show that the amplitude \( A(\omega) \) is given by

\[
A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{i\omega t} \left[u(0,t) - \frac{i}{k_z(\omega)} \frac{\partial u}{\partial z}(0,t)\right] dt
\]

(2)

We assume

\[
\nu(0,t) = S(t) \sin\left[(\omega_0 - \omega_0 \beta t) t\right]
\]

(3)

as the initial shape of the pulse. Here shape function \( S(t) \) has been taken as Gaussian as well as a step function. The parameter \( \beta \) is the measure of frequency variation with time. Substituting Eq. (3) in Eq. (2) we get \( \nu(z,t) \). The numerical results are given in next section.

3. Results

In this section, we examine the operation of helically corrugated waveguide for given set of parameters: Mean radius \( R_0=1.47 \text{cm} \), corrugation period \( z_0=2.89 \), corrugation amplitude \( h=0.19 \text{cm} \), three fold periodicity \( q_0=3 \), and \( \beta=0.01 \text{ ns}^{-1} \).

Figure. 3 Dispersion diagram of the helical waveguide. Central frequency 9.3 GHz is considered
In Fig. 3, frequency as a function for TE_{11}-TE_{21} (coupled first and zeroth floquet harmonic) is given for the chosen parameters. In the neighborhood of frequency 9.3 GHz, decrease in frequency increases the group velocity of the mode. In a pulse whose frequency decreases with time, the tail will move faster, resulting into the compression of pulse.

In Fig. 4, pulse compression for two different pulse profiles are given. In Fig. 4(a), shape function $S(t) = e^{-\alpha_0(\tau-t_0)^2}$, $t_0 = 20$ ns is considered. The frequency sweep parameter $\beta=0.01$ ns$^{-1}$. The input pulse is shown in blue. After propagating 110 cm, the pulse gets compressed shown in red. In Fig. 4(b), step shape function is considered. The pulse width is 40 ns and the frequency sweep parameter $\beta=0.02$ ns$^{-1}$. The input pulse and output pulse after propagating 110 cm, are shown in blue and red, respectively. An eleven fold peak power compression is obtained.

4. Conclusion
Helically corrugated waveguide dispersion relation is solved. Pulse compression studied for Gaussian as well as rectangular pulse. Seven fold in former and eleven fold power increase in latter case, is obtained. The numerical results are in agreement with the experimental results of G. Burt et. al.[4].

References
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