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Tunable compression of THz chirped-pulses using a helical graphene ribbon-loaded hollow core waveguide

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Pulse-shaping is important for communications, spectroscopy and other applications that require high peak power and pulsed operation, such as radar systems. Unfortunately, pulse-shaping remains largely elusive for terahertz (THz) frequencies. To address this void, a comprehensive study on the dispersion tunability properties of THz chirped pulses traveling through a dielectric-lined hollow-core waveguide loaded with a helical graphene ribbon is presented. It is demonstrated that there is an optimal compression waveguide length over which THz chirped pulses reach the maximum compression. The optimal length is dependent on the chirp pulse duration. It is shown that by applying an electrostatic controlling gate voltage (V_g) of 0 and 30 V on the helical graphene ribbon, the temporal input pulses of width 8 and 12 ps propagating through two different lengths can be tuned by 5.9% and 8%, respectively, in the frequency range of 2.15 THz - 2.28 THz. © 2020 Optical Society of America

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1. INTRODUCTION

THz technology is of particular interest as the next frontier for the future short-range high-speed wireless link [1] and the upcoming mobile networks beyond 5G [2], as more bandwidth-hungry applications are waiting for a feasible protocol solution [3]. By moving system carrier frequencies beyond 0.1 THz, such ultra-high bandwidths can be provided. Technology for such range is steadily shifting from university grade instrumentation to commercial systems [4]. However, a key component for communication systems, the pulse-shaper, remains elusive outside the lab [5–7]. Frequently, temporally short pulses are realized with linear dispersion [8] or nonlinear dispersion [9] compression using external dispersive elements that have large chromatic dispersion. This function might be performed by a variety of photonic components such as gratings [10], prisms [11], chirped-mirrors [12] and gas-filled hollow-core fibers

[13]. Nevertheless, they lack tunability, which is crucial for communication applications, and may be difficult to integrate with commercial systems. A promising solution may rely on low-loss dispersion-tunable waveguides, wherein graphene with excellent tunability at THz frequencies [14–16] is exploited. Such a waveguide can be realized with helically-corrugated circular waveguides which have been successfully used for “gyro” applications [17], whose helical corrugation is a hybrid metal-graphene ribbon that allows electrical tunability.

In this study, we explore the possibility of the linear compression of chirped pulses in the positive group velocity dispersion (GVD) region of a dielectric-lined circular waveguide loaded with a helical graphene ribbon (Fig. 1). We will show that the proposed structure introduces a good tunability of the compression factor via the graphene electrostatic bias. The dielectric-lined circular waveguide is cho-

sen not only because of its low loss response [18, 19] and easy implementation of the DC voltage controlling of helical graphene ribbon, but also because, unlike open-waveguides, it enables the removal of the strong THz atmospheric absorption by purging the waveguide.

2. NUMERICAL MODELING AND SIMULATION SETUP

A. Model geometry and proposed fabrication approach

Figure 1 shows the 3D-geometry and side view of the proposed graphene ribbon loaded waveguide: a graphene ribbon with thickness t_{gr} , ribbon width w , and pitch size p is helically wrapped and inserted inside a metalized dielectric tube of thickness t_d . By carefully choosing the geometric parameters, the dielectric material, and the DC-controlling bias, an optimum condition for an arbitrary dispersion profile, large mode confinement, minimum mismatch, and propagation loss with maximum tunability can be achieved. The length of the waveguide section loaded with the helical graphene-ribbon is L_0 . As shown in the side view illustration of the yz -plane, the two ends of the waveguide are tapered sections to ensure the lowest possible return loss when interfacing the THz pulse compressor with a standard smooth circular waveguide. These identical sections are two simple conical circular waveguides of length L_2 that gradually connect the helix to the ends of L_1 -long circular waveguides.

The optimized dimensions of the proposed tunable graphene-based waveguide are listed in Table 1. Recent progress in the fabrication of graphene-based devices [20] has shown that our proposed structure, with the dimensions of Table 1, could be realized in various ways. The fabrication methods can be broadly categorized as micro-mechanical exfoliation [21], chemical vapor deposition (CVD) [22, 23], epitaxial growth [24], and the reduction of graphene oxide [25]. Out of various techniques mentioned, CVD has proven to be the most promising approach for the growth of graphene [26]. Cylindrical multi-layered graphene-based structures could be synthesized in two suggested ways: (i) the graphene sheet or ribbon is produced using one of the above techniques, then rolling up [27, 28] on a dissolvable polymer rod such as PMMA (Polymethyl methacrylate) and finally removing the unwanted areas using an effective PMMA-solvent like acetone [29], (ii) CVD

Fig. 1. Schematic-diagram, 3D-geometry, and side-view of an internally dielectric-coated hollow-core waveguide loaded by a helical graphene ribbon (Inset: the graphene ribbon is grown on a thin SiO₂ layer and sandwiched between two gold ribbons to facilitate the DC-controlling of the device).

growth of graphene on a gold film which is helically patterned on a PMMA-rod by lithography technique. Then, the hollow core waveguide will be achieved by removing the PMMA with the help of acetone. The Au-ribbon used for applying the external controlling DC voltage could be formed by lithography process. Moreover, HDPE could be realized by using a polymer coating solution. Au-cladding could be performed as the final step by simple metal-coating [30].

B. Materials

High-density polyethylene (HDPE) is used for the dielectric tube given its good THz transparency ($n = 1.524$, and $\alpha = 0.2 \text{ cm}^{-1}$ at 1 THz [31]). The dielectric tube is completely covered by a gold film layer as a metal cladding. Gold is modeled with the Drude parameters as follows [32]: $\epsilon_\infty = 9.1$, $\omega_p = 1.38 \times 10^{16} \text{ rad/s}$, and $\Gamma = 1.075 \times 10^{14} \text{ Hz}$. In addition, the graphene layer can be considered as a 2D single layer material of thickness 0.4 nm - 1.7 nm [33]. In the THz frequency range, especially that below the electron-phonon interaction frequency ($< 7.3 \text{ THz}$), the graphene is well modeled by the Kubo formula and can be described by a complex constant ϵ_g [34]. The complex permittivity of ϵ_g is a function of the angular frequency ω , temperature T , chemical potential μ_c (or Fermi-level E_F), and the relaxation time τ . The

well-known Drude equivalent model of graphene is as follows:

$$\epsilon_g(\omega) = 1 + i \frac{\sigma_s^{intra}(\omega)}{\epsilon_0 \omega t_{gr}}, \quad (1)$$

$$\sigma_s^{intra} = \frac{2k_B T e^2}{\pi \hbar^2} \ln(2 \cosh \frac{\mu_c}{2k_B T}) \left(\frac{i}{\omega + i\tau^{-1}} \right), \quad (2)$$

The relaxation time is calculated according to the formula $\tau = \mu E_F / e v_F^2$ where μ is the carrier mobility of graphene, v_F is the Fermi velocity, e is electron charge, and E_F is Fermi energy level [35]. The carrier mobility value depends on the fabrication method of graphene. Here, we use moderate Fermi energy level of 0.5 eV. The carrier mobility and the Fermi velocity are chosen to be $10000 \text{ cm}^2 / \text{V.s}$ and 10^6 m/s , respectively.

C. Electrostatic bias vs. Fermi-level

The graphene ribbon lies on a thin SiO_2 layer ($\epsilon_r = 3.9$ and $\tan \delta = 0.0056$ [36]) with thickness t_{SiO_2} . An internal helical narrow gold film (w_{gold}) and the fully covered back gold films facilitate the required DC-controlling bias of the graphene ribbon. The Fermi level E_F can be controlled over a wide range by applying a transverse electric field using a gate voltage V_g . An approximate expression to relate E_F and V_g is given by $V_g = E_F^2 q_e t_{\text{SiO}_2} / \pi \epsilon_0 \epsilon_{\text{SiO}_2} (\hbar v_F)^2$ [37], where q_e is the electron charge, v_F is the Fermi velocity, and $\hbar$ is the reduced Plank's constant. Generally, the Fermi-level can be tuned within the range from -1.0 eV to 1.0 eV, but due to negligible variation of the group velocity for E_F greater than 0.5 eV, such a value of E_F is considered the maximum. The typical values of V_g that ensures the safe bias electrostatic fields on the order of several volts per nanometer applied on the graphene are in the range of 0-100 V. Figure 2, shows how V_g changes with E_F for different t_{SiO_2} . Therefore, for a safe maximum bias of about 30 V, the thickness of t_{SiO_2} has been chosen as 150 nm.

D. Numerical Method

Except for a few cases, hybrid waveguides such as that proposed here cannot be modeled analytically. Hence, the finite integral technique (FIT) is used here [38]. By carefully choosing the geometric parameters, a dispersion DC-controlled pulse compressor with large mode confinement, minimum mismatch, and

Fig. 2. The DC controlling voltage V_g vs. Fermi-level E_F in terms of various SiO_2 thickness.

Table 1. The optimal geometrical dimensions of the proposed graphene-based pulse compressor.

R	p	w	w_{gold}	t_{gold}
100 μm	126 μm	42 μm	30 μm	1 μm
t_{SiO_2}	t_d	t_{gr}	L_1	L_2
150 nm	7.5 μm	100 nm	40 μm	100 μm

low propagation loss is designed. Meshing a complex geometry including a dispersive infinitesimal thin layer such as graphene is an essential part of the simulation. Thus, after a convergence test, we have chosen a graphene thickness of $t_{gr} = 100 \text{ nm}$ as the minimum cell size for the helix ribbon, while the material properties of graphene were defined based on its real thickness of 1 nm. Due to computational constraints, a smaller graphene thickness was not viable. This tradeoff approach is commonly found in the literature [39]. The default mesh line limit is set at 10 lines per wavelength, resulting into 3,958,080 and 12,533,920 hexahedral mesh units for the 720 μm - and 1700 μm -long pulse compressor, respectively.

3. RESULTS AND DISCUSSION

A. DC-controlled Dispersion Mechanism

The inner dielectric layer of the circular waveguide and the helical graphene ribbon provide the main functionality in the proposed graphene-based pulse compressor. The propagation characteristics of an electromagnetic structure can be studied with two common approaches: one is directly focused on circuit theory using the equivalent circuit model, and the other is based on electromagnetic mode analysis.

Fig. 3. (a) Magnitude and (b) phase of the S-parameters of the proposed device biased at $V_g = 0$ and 30 V.

The circuit model of the helical waveguide can be expressed by one inductance per unit length and two radial and inter-turn capacitances per unit length [40, 41]. Thus, a strong dispersion due to helix-shield capacitive coupling voltages and helix equivalent inductive currents can be introduced. This effect mainly depends on the dielectric tube parameters (t_s , ϵ_d) for the former, and the helix characteristics, (σ_g , w , p) for the latter. The dependence of the propagation constant in optical and RF waveguides, including shape and size and inner-coating material layer has been explored and shown in articles [42–44]. In principle, the mode propagation constant can be obtained from the dispersion equation solved from electromagnetic field solutions. The numerical analysis for tackling such these problems is reportedly available in the literature [43, 44]. In simple structure such as an internally-coated circular waveguide with a lossy layer, approximated analytical solutions of the characteristic equation in studying the physical features of the propagation constants have been presented in [43]. In this case, Luo and et. al,

Fig. 4. (a) Group velocity dispersion (GVD), (b) normalized group velocity, and (c) the real and imaginary parts of the effective refractive index of the proposed device biased at $V_g = 0$ and 30 V.

show how the variation of the lossy layer thickness (t) affects on the propagation constants for all five modes (TE_{11} , TM_{01} , TE_{21} , TM_{11} , and TE_{01}). When is great when ($t/\delta < 1.5$ where δ is the skin depth of electromagnetic waves in the good conductor while for $t/\delta > 2.5$ the propagation constants will become stable. Rao [44], using boundary value method has obtained the dispersive equation of a circular waveguide that is coated on the inside with a metamaterial and compared with a dielectric coated one. He shown that the variation of the normalized phase constant (β/k_0) with frequency, for dielectric ($\epsilon_r > 0$, $\mu_r > 0$) and metamaterial coating ($\epsilon_r < 0$, $\mu_r < 0$) is exactly opposite. In conclusion, when a circular waveguide loaded with a dielectric-coated helically wrapped Graphene ribbon, which is a material with $\text{Re}[\epsilon_r] < 0$ and $\text{Im}[\epsilon_r] > 0$, we can expected that shows a high dispersive phenomena which is interesting for passive pulse compression.

The influences of the Fermi level on the propagation properties are depicted in Fig. 3 and 4. The pulse-shaper component has a good matching and low insertion loss (an average of -1.4 dB) in a bandwidth > 200 GHz around the center frequency of 2.15 THz and it is independent of the graphene bias. The spectral phase response of the structure shows a tunable phase change in terms of the applied DC-voltage (Fig. 3(b)).

The GVD and normalized group velocity of the component is illustrated in Figs. 4(a) and (b), respectively, where the Fermi-level of the graphene ribbon changes in the range of 0.0 eV (non-biased) and 0.5 eV ($V_g = 30$ V). For Fermi-level $E_F = 0.5$ eV, the waveguide simultaneously shows negative and positive GVD responses at 2.06 - 2.15 THz and 2.15 - 2.28 THz, respectively. The reason behind this phenomenon can be explained by the fact that when the effective permittivity of the graphene ribbon changes with the increase of the Fermi-level, the aforementioned equivalent capacitances and inductances of the structure can manipulate the traveling wave in a dispersive manner. Secondly, as the overall wavefront inside a metallic hollow waveguide has been formed by successive reflections from the inner walls of the waveguide, one can expect the presence of a very high chromatic dispersive structure such as a helical graphene ribbon to be able to manipulate the phase of the resultant propagation mode. For completeness, Fig. 4(c) $Re(n_{eff}) = \beta/k_0$, where k_0 is the free space wave number and β is the wave propagation constant, and $Im(n_{eff})$. The former encapsulates the group velocity and group velocity dispersion, whereas the latter accounts for the loss. Notice that $Im(n_{eff})$ is easily computed via the absorption coefficient $\alpha = 2k_0 Im(n_{eff})$ [45], which is estimated from the scattering parameters $|S_{21}|$ and $|S_{11}|$ shown in Fig. 3.

B. Pulse compression

In order to investigate the pulse compression performance of the component, it is assumed that the input pulse is a y-polarized chirped sine function, as stated in Eqn. (3), where f_{Hi} is the upper-band frequency of the negative dispersion region, T_0 is the input pulse width, E_0 is the electric field amplitude and μ is the chirp factor. The chirp factor for a uniform input pulse spectrum in the positive GVD region from f_{Lo} to f_{Hi} , respectively here from 2.15 THz to 2.28 THz,

can be calculated using Eqn. (4).

$$E_y = \begin{cases} E_0 \sin(2\pi f_0 t - \mu t^2), & \text{if } t \leq T_0 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$\mu = \frac{2\pi(f_{Hi} - f_{Lo})}{T_0} \quad (4)$$

The instantaneous frequency which can be obtained from the time derivative of the phase argument of Eqn. (3), proves that the tail of the chirped pulses with low-frequency components, with faster group velocities, will move to overtake the front high frequencies components of the pulses, resulting in temporal pulse shortening with growth in amplitude. To validate the performance of the device and highlight the presence of a unique optimal length for each arbitrarily selected pulse width, two optimal compression lengths corresponding with the two chosen pulse widths of 8 ps and 12 ps have been numerically obtained as 720 μm and 1700 μm , respectively. The optimization goals in our design are the maximum compression ratio and the minimal residual pulse pedestal which ensure a high-quality compression. Figure 5 and 6, show the temporal waveform evolution of the envelope of the device for these two optimal lengths, 720 μm and 1700 μm , for the two bias states, zero-bias and 30 V. An important conclusion is that the pulse compressor functionalities can be controlled with a feasible gate voltage V_g . Figures 7 and 8, compare the pulse compression performance of the device in the time and frequency domains for both studied optimal lengths. It can be seen that with increasing structure length, a high quality temporal compressed pulse (negligible pedestal and large full-width at half-maximum (FWHM)) can be achieved. Additionally, the compression rate can easily be tuned via the gate voltage, V_g . The mode patterns of the device are shown in the inset of the spectrum plots. These patterns show that the mode confinement can be tuned via two factors which are the graphene electrostatic bias and the length of the structure. One of the important parameters in the pulse compression applications is the broadening factor (F) which is defined as the ratio of FWHM of the compressed pulse to the FWHM of the input pulse. Table II summarizes the broadening (ΔFWHM) of two studied model lengths and their tuning percentages, which is defined as the percentage of the broadening change. This parameter

Fig. 5. The waveform evolution of the proposed device with the optimal length of 720 μm , corresponding to an input pulse duration of 8 ps, based on two border values of controlling DC voltage (a) 0 V, and (b) 30 V.

is also known as the modulation depth defined by $(\Delta F/F_0) \times 100\%$, where ΔF is the changes of F due to $\Delta V_g = 30$ V, and F_0 is the average of the minimum and maximum obtainable F [46]. To the best of our knowledge, no studies have examined the combination of graphene and pulse compression techniques in the THz regime. It is helpful, however, to review the literature to quantitatively justify our work. In [47], a THz passive pulse compressor shows a 2 ps, 0.5 THz chirped pulse after transmission through a 10 μm circular aperture in a gold-film-GaAs. The pulse was compressed to 1.4 ps with ΔFWHM of 0.07 THz. One of the major drawbacks of this structure is the extremely low output to input peak intensity ratio of 3.7×10^{-5} . Another example is direct compression of ultra-fast laser pulses using a dispersive and nonlinear thick (550 μm) cholesteric liquid crystal sample [48]. After passing the laser pulses

Fig. 6. The waveform evolution of the proposed device with the optimal length of 1700 μm , corresponding to an input pulse duration of 12 ps, based on two border values of controlling DC voltage (a) 0 V, and (b) 30 V.

Table 2. The tuning percentage of the proposed graphene-based pulse compressor.

Model Lengths	720 μm	1700 μm
$\Delta\text{FWHM} @ V_g = 0.0$ V	3.96 GHz	12.20 GHz
$\Delta\text{FWHM} @ V_g = 30$ V	1.11 GHz	9.46 GHz
Tuning%	5.9%	8.04%

across this material, a broadening of 1.8 THz around the center frequency of 387 THz (777 nm) has been achieved. Comparing the numerical results shown in Table II with the literature, one can conclude that the proposed graphene-based tunable pulse compressor holds promise for THz applications.

Fig. 7. (a) Time and (b) spectral descriptions of the pulse compressor output for $V_g = 0$ V and 30 V for a length of $720 \mu\text{m}$ (the mode patterns at the end of the helix are presented in the insets of the figure).

4. CONCLUSION

In this paper, it was demonstrated that the tunable chromatic dispersive properties of a helical graphene ribbon can be exploited in a compact waveguide component to generate a DC-controlled compressed pulse. By using this graphene-based waveguide controlled by a DC-voltage V_g , in the range of 0 V to 30 V, it was possible to generate a high quality tunable compressed THz pulses from a chirped pulse input. Two optimal lengths of $720 \mu\text{m}$ and $1700 \mu\text{m}$ were obtained corresponding with the two input pulse time durations of 8 ps, and 12 ps, respectively. It was concluded that both of the broadening and the quality of the compressed pulse were simultaneously improved by increasing the optimal length (or equivalently the pulse duration) and controlling the voltage V_g (or equivalently the Fermi-level of the graphene). Moreover, the proposed THz device provided significant tuning percentages of 5.9% and 8.04% for the

Fig. 8. (a) Time and (b) spectral descriptions of the pulse compressor output for $V_g = 0$ V and 30 V for a length of $1700 \mu\text{m}$ (the mode patterns at the end of the helix are presented in the insets of the figure).

optimal lengths of $720 \mu\text{m}$ and $1700 \mu\text{m}$, respectively. This work paves the way toward the next generation of communication system and THz spectroscopy.

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6. DISCLOSURES

The authors declare no conflicts of interest.

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