DOI: https://doi.org/10.1109/TAP.2014.2346708

Meander Dipole Antenna to Increase CW THz Photomixing Emitted Power

Javier Montero-de-Paz, Eduardo Ugarte-Muñoz, Luis Enrique García-Muñoz, Iván Cámara Mayorga, Daniel Segovia-Vargas, *Member, IEEE*

***Abstract*—The success in conquering the Terahertz (THz) gap is subject to some facts such as maximizing the emitted power. Traditionally resonant antenna designs for Continuous-Wave (CW) THz photomixing include a RF choke to compensate the capacitive part of the photomixer and an antenna with a very high input impedance at its resonance to match the low value of the photomixer conductance. This paper considers that the antenna itself can provide this large impedance margin needed to directly match the photomixer, so that the RF choke can be avoided. The meander antenna constitutes an excellent candidate to achieve that goal based on the Active Integrated Antenna concept to improve both matching and radiation efficiencies. The main objective is to maximize the total efficiency and, as a consequence, the THz emitted power. A prototype working at 1.05 THz is designed and manufactured and results show a 6 dB output power improvement when compared with a conventional log-periodic antenna.**

***Index Terms*—Active Integrated Antenna, CW Photomixing, Meander Dipole Antenna, THz**

I. Introduction

MAXIMIZING THz emitted power is one of the hot topics in the electronic and photonic communities nowadays [1], [2]. THz waves have been presented as one of the most promising research lines due to its unique capabilities. Extremely short pulses, capable of obtaining high spatial resolutions, going across light opaque materials and visualizing and identifying microscopic structures by spectral analysis, can be generated. Theoretically THz waves can find a lot of applications that range from radioastronomy, to imaging, security, biomedical, industrial, etc [1]. However, the low power that current devices can generate at these frequencies is the main drawback that these applications are finding to be developed. The power increase at THz frequencies in room temperature is then a key issue [3].

Two main approaches are being followed to generate THz waves at room temperature [1]. The first one is a purely electronic approach based on up-conversion [4] while the second one consists on an electro-optical down-conversion ("photomixing" [5]). In addition, direct quantum mechanical frequency generation (QCLs [6]) is a well established THz source. Unfortunately, nowadays it cannot work at room temperature [7]. Another interesting approach to generate THz CW power is the Large Area Emitter (LAE) concept [8]. This is an antenna-free new scheme of photomixing where the THz radiation is directly originated from the acceleration of photo-induced charge carriers generated within a large semiconductor area.

Photomixing is nowadays one of the most commonly used systems to generate CW THz signals due to its broadband nature and its reasonably high output power. It consists of two lasers working at two different frequencies ω_1 and ω_2 which are spatially overlapped to generate a THz beatnote. These lasers are then used to illuminate an ultrafast semi-conductor material (III-V family) such as GaAs. An applied electric field allows the conductivity variation to be converted into a current which is radiated by an antenna. The frequency of this current is the difference between both laser frequencies ($\omega_{THz} = \omega_1-\omega_2$). A typical CW THz photomixing emitter consists on a semiconductor device (photomixer), a planar antenna (broadband or resonant one depending on the application) and a silicon hyper-hemispherical lens to increase the directivity and avoid substrate reflections [9]. Traditionally, photomixing is used in broadband applications such as spectrometry because of its high frequency tunability, so broadband antennas are preferred. However, it is also utilized as signal generator for LO on receivers [10]. In that case, a resonant antenna would be more suitable.

In [11], authors proposed a methodology to design resonant antennas to increase output power, which is the one that researchers designing THz photomixer based antenna emitters traditionally follow [10],[12]. Photomixers have a relatively high capacitive susceptance that is compensated with a RF choke. In addition, they exhibit a very low conductance value (typically lower than $(10k\Omega)^{-1}$), so a resonant antenna with a very high input impedance at its resonance would be desirable. With this approach, at least two components should be separately designed to be finally joined together: the RF choke and the antenna. Several attempts have been followed to design antennas with a very high value of its input impedance at its resonance [11],[12] to be included in CW THz photomixing devices. But all of them include the RF choke to compensate the capacitive susceptance, so the design of the overall structure is somehow complicated.

In this paper we propose for the first time in the THz gap the meander dipole antenna [13] as a solution to compensate both the capacitive susceptance and the conductance of the photomixer in a single element. The antenna design approach is based on the Active Integrated Antenna (AIA) concept [14], [15] to improve both the matching and the radiation efficiencies. The novelty of this work is that we forced the meander dipole antenna to work out of its main resonance, at lower frequencies, where it exhibits a clearly inductive behaviour. The proposed antenna design can be followed independently of the photomixer used and it consists on trying

Manuscript received 21, February, 2014. The work of J. Montero-de-Paz was supported by the Spanish Education Minister under the program FPU (AP2009-4679). The work of E. Ugarte-Muñoz was supported by the Spanish Economy Minister under the program FPI (BES2010-037676). This work was also supported by Consolider CSD 2008-00068.

J. Montero-de-Paz, E. Ugarte-Muñoz, L. E. García-Muñoz and D. Segovia-Vargas are with the Departamento de Teoría de la Señal y Comunicaciones, Universidad Carlos III de Madrid, Leganés, 28911 Spain (phone: +34 916246214; fax: +34 916248749; e-mail: jmontero@ tsc.uc3m.es, legarcia@tsc.uc3m.es, dani@tsc.uc3m.es).

I. Cámara Mayorga is with the Max-Planck-Insitut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany (e-mail: imayorga@mpifr-bonn.mpg.de)

to maximize the radiated power obtained from it. This same approach has also been followed in [16] with the design of a millimetre-wave Quasi-Optical Schottky Barrier Diode receiver. Unfortunately, the mismatch obtained with a broadband antenna in that case was not that huge, so little improvement was achieved.

The paper is organized as follows. After this brief introduction, the CW THz emitter structure is presented. The photomixer with its equivalent circuit and its main parameters will be shown. Next section will be devoted to describe the meander dipole antenna and its behaviour. Matching, radiation and total efficiencies will be calculated and a final design working at 1.05 THz will be presented and compared with a similar log-periodic based CW THz emitter. Finally, both meander dipole and log-periodic antenna emitters are manufactured to compare the performance of both of them.

II. CW THz Generation by Photomixing

As outlined in the introduction, in the traditional approach for CW THz generation by photomixing a THz current is generated in a semiconductor device using two heterodyned laser beams of photon energies $\hbar(\omega_0 \pm \omega_{THz}/2)$ (with the same power, $P_L/2$, and polarization), differing in photon frequency by the THz frequency ω_{THz} (being h the Planck constant and ω_0 the central frequency). As a first step, the heterodyned laser signal is absorbed on typical length scales shorter than 1 µm, i.e. much shorter than the THz wavelength. In the second step the resulting photocurrent is fed into an antenna, which then emits THz radiation [5]. A typical schematic of the CW THz generation by photomixing device, can be seen on Fig. 1.

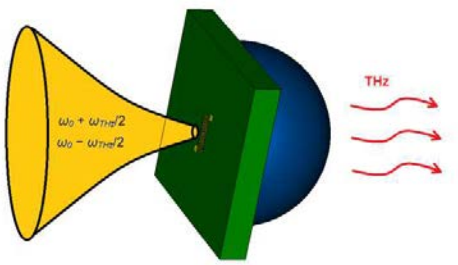


Fig. 1. Schematic of the CW THz photomixing antenna emitter. Two optical lasers impinge in the photomixer device which is integrated with an antenna over GaAs substrate (green part). A silicon lens (blue part) is included to avoid substrate reflections and increase directivity [9].

An interdigitated LT-GaAs based photomixer is used as the non-linear device to generate the THz signal. It consists of eight interdigitated fingers, with a finger gap = 1 µm, and finger width = 200 nm. Fig. 2(a) shows a SEM photograph of the device. The small-signal equivalent circuit of Fig. 2(b) [11] is obtained, being C = 2fF the parasitic capacitance from the fringing fields between the 200 nm wide fingers and $G = (10k\Omega)^{-1}$ the conductance given by I_{DC}/V_{DC}. The antenna admittance ($Y_a(\omega)$) is also included in the equivalent circuit of Fig. 2(b).

III. Meander Dipole Antenna Design

From the antenna point of view only two parameters can be optimized in order to maximize the THz emitted power: the radiation efficiency (ε_{rad}) and the mismatching factor (M). The mismatching factor is defined with the M-factor given by [17]:

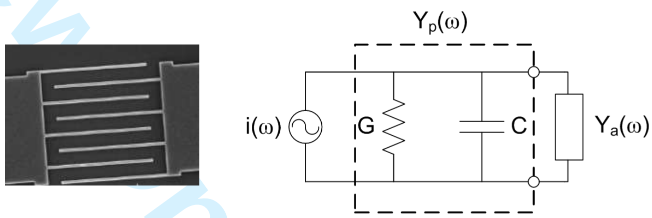
$$M = \frac{4R_a R_p}{\left(R_a + R_p\right)^2 + \left(X_a + X_p\right)^2} \qquad (1)$$

where $Z_a=R_a+jX_a$ is the input impedance of the antenna and $Z_p=R_p+jX_p$ is the input impedance of the photomixer.

The antenna efficiency can then be defined as the product of these two efficiencies and the polarization efficiency (ε_{pol}) [18]:

$$\varepsilon_{ant} = \varepsilon_{rad} \cdot M \cdot \varepsilon_{pol} \qquad (2)$$

This efficiency expresses how far the system is from the ideal behaviour of the emitter. Maximizing this efficiency will enhance the performance of the emitter and it is the key factor that we have used to optimize the design of the antenna. This design is based on the AIA concept ([14],[15]) and tries to maximize the antenna efficiency as defined in Eqn. (2). In its design, both mismatching factor and radiation efficiency must be considered. With the photomixer parameters mentioned before, the input impedance ($Z_p(\omega)=1/Y_p(\omega)=1/(G+j\omega C)$, Fig. 2(b)) is found to be 0.57-j75.8 at 1.05 THz, so an antenna with an input impedance of 0.57+j75.8 at that frequency will maximize the Eqn. (1). This low value of the real part and relative high value of the imaginary part are very difficult to be simultaneously obtained with a simple resonant antenna.



(a) (b)

Fig. 2. (a) SEM photograph of the interdigitated LT-GaAs photomixer and (b) its equivalent circuit.

Meander dipole antenna is similar to a dipole where its radiating part is bent to a meander shape in order to reduce the antenna size [13]. A schematic of it with its main design parameters can be seen on Fig. 3(a). Traditionally, this antenna is used to reduce the antenna size (antenna miniaturization) and in systems that need a very high value of the input impedance, since this antenna provides higher values of input impedance at its resonance (Fig. 3(b)) than λ-dipoles or dual-dipoles [13]. In the THz region, this antenna has been used under the name of "folded dipole" to obtain a very high input impedance [19]-[22]. In all previous works, the antenna is working at its main resonance frequency (thus showing a high resistive input impedance). None of them try to maximize the M-factor and no attention is focused neither in the imaginary part of the input impedance nor the radiation efficiency. The novelty that we have pursued in the present work with the meander dipole antenna rises from using it out of its main resonance region [15], as at lower frequencies than its resonance it exhibits a low real part and an inductive behaviour (shown in Fig. 3(b), frequency range from 0.9 THz to 1.3 THz) suitable for matching it with the photomixer capacitive behaviour. With such design, we expect to achieve a conjugate matching between the antenna and the photomixer without any additional element, increasing the mismatching factor. The antenna will show the optimal input impedance to the photomixer, so an integrated active antenna is obtained [14]. According to [14] and [15], this design philosophy will improve the system parameters and the merit figure of the overall transmitter.

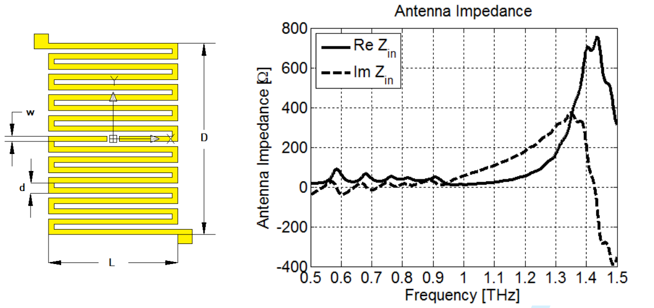


Fig. 3. Meander dipole antenna: (a) Schematic and main parameters. (b) Simulated input impedance of a meandered dipole antenna over semi-infinite silicon substrate with parameters: L = 37 µm, w = 3.5 µm, d = 2 µm, D = 105.5 µm and 9 bends per arm.

A. *Parametric study*

In order to analyze the effect of each parameter on the antenna efficiency, several simulations have been done and results can be seen on Fig. 4 and Fig. 5. Full-wave electromagnetic simulator CST Microwave Studio has been used in order to carry out the simulations. Silicon semi-infinite substrate was set as background material in order to reduce computational time [12]. Both the mismatching factor and the radiation efficiency are shown, as well as the antenna efficiency (Eqn. (2), assuming $\varepsilon_{pol} = 1$).

The design parameters of the meander dipole antenna are (see Fig. 3(a)): the length (*L*), the width (*w*) of the arms, the separation between them (*d*) and the number of bends. Some conclusions can be extracted from these simulations. *L* parameter changes the resonant frequency of the meander antenna: the higher the value of *L* the lower the resonant frequency (larger size of the antenna). In addition, the closer the lines of the meander dipole antenna (lower value of *d*), the lower the radiation efficiency. This is due to the fact that currents have opposite directions so they cancel each other [13]. It is important to keep enough space between lines in order to have a relatively high value of the radiation efficiency. Regarding the number of bends, it has been noticed that for a number of bends higher than 3 (total length of the dipole > 2λ), neither the input impedance nor the radiation efficiency change significantly. Finally, *w* does not have an important role in both efficiencies and can be kept constant on optimization.

It is important to highlight that radiation efficiency keeps a relatively high value up to frequencies lower than 2/3 of its main resonance frequency. In all the above simulations, main resonance is located somewhere close to 1.5 THz (see Fig. 3(b)) and our design frequency is 1.05THz.

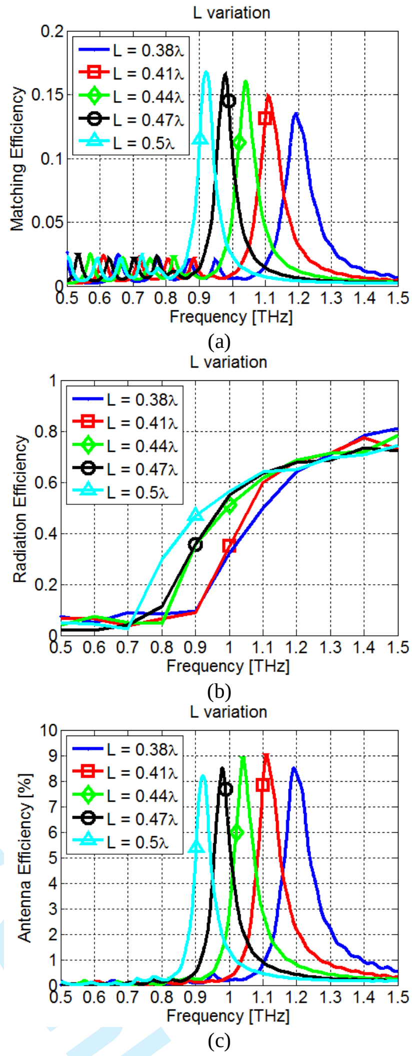


Fig. 4. L variation. (a) Matching efficiency, (b) radiation efficiency and (c) antenna efficiency. w = 0.044λ, d = 0.08λ.

IV. 1.05 THz PROTOTYPE

Finally, a prototype working at 1.05 THz as a LO for a radioastronomy heterodyne detector [10] was designed and manufactured. The main parameters are *L* = 37 µm, *w* = 3.5 µm, *d* = 2 µm, *D* = 105.5 µm and 9 bends per arm (Fig. 6). Separation between the middle arm and the following next (up or down) was fixed to 3.5 µm to keep enough space for the photomixer device. Simulated input impedance can be seen on Fig. 3(b). With such antenna an antenna efficiency of 7.05% at 1.05 THz is estimated, with matching and radiation efficiencies equal to 14.73% and 47.83% respectively. For the sake of comparison, a self-complementary log-periodic antenna [18] was designed and its antenna efficiency calculated. Its maximum and minimum dimensions are 200 µm and 10 µm respectively. In contrast with the meander dipole design, broadband antennas exhibit an almost constant impedance with frequency (self-complementary antennas: $60\pi/\sqrt{\varepsilon_r}$ for the real part and 0 for the imaginary part [17]), so little improvement can be achieved in the matching efficiency. In this second antenna emitter, an antenna efficiency of 1.73% is estimated with matching efficiency equal to 2.01% and radiation efficiency equal to 86.03%. Fig. 7 shows the simulated power improvement obtained with the meander dipole antenna emitter given by $\varepsilon_{ant}^{meander} / \varepsilon_{ant}^{\log-per}$. A 6 dB improvement at 1.05 THz is expected with the meander dipole antenna.

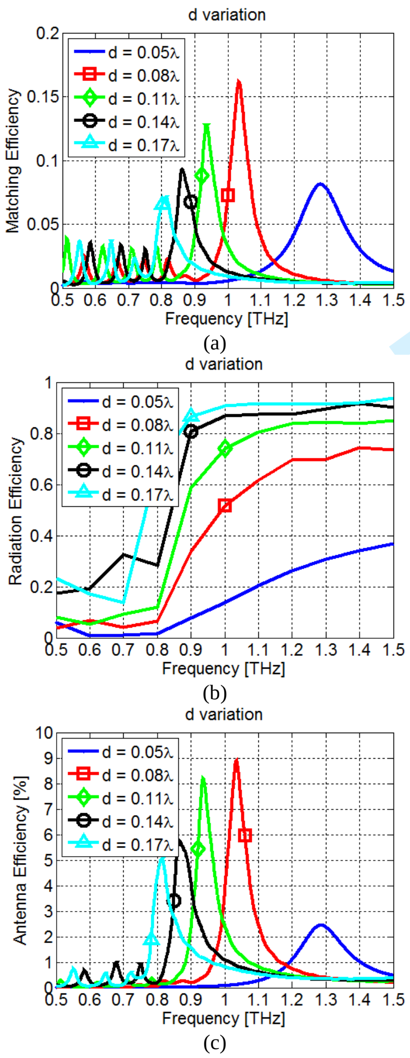


Fig. 5. *d* variation. (a) Matching efficiency, (b) radiation efficiency and (c) antenna efficiency. w = 0.044λ, L = 0.44λ.

Two antenna emitters, one with the meander dipole antenna and other with the log-periodic antenna were manufactured. In both of them, the same photomixer structure (Section II) and the same lens (10 mm diameter hyperhemispherical high resistivity silicon lens) were used. It is worth to highlight that the main challenge with the meander dipole antenna is that it is a highly resonant antenna, so a small variation in the manufacturing process or in the permittivity of the material would change its performance.

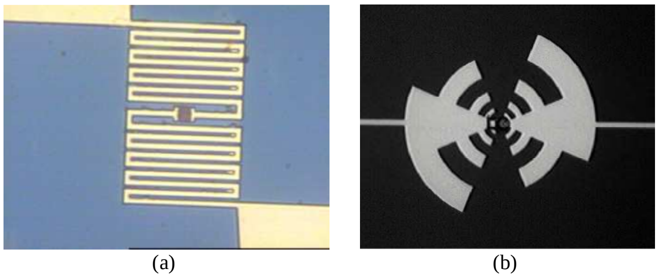


Fig. 6. Photograph of the manufactured antennas integrated with the LT-GaAs photomixer device. (a) Meander dipole antenna and (b) Log-Periodic antenna.

A typical CW THz photomixing measurements setup was utilized to characterize the emitted power. It consists of two 850 nm lasers that illuminate the photomixer device. THz frequency is tuned and THz emitted power is measured from 80 GHz up to 2 THz. The photomixer output THz frequency depends on the frequency of the two lasers impinging over it. In the measurements shown in Figure 8, the frequency of one of the lasers remains constant while the other is changed to obtain the desired output THz frequency. This frequency change can be done either by modifying the current or the temperature of the laser. The THz radiation emitted by the antenna with the lens is, first, chopped with an optical chopper and then beam focused with two parabolic mirrors. The THz signal impinges a diamond window Golay cell connected to a lock-in amplifier which uses as the reference signal the chopper one. Measured output power with both meander and log-periodic antenna emitters are shown in Fig. 8.

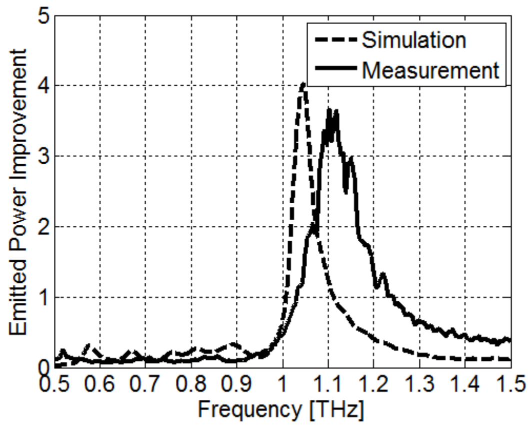


Fig. 7. Emitted power improvement when comparing meander dipole antenna with log-periodic antenna ($\varepsilon_{ant}^{meander} / \varepsilon_{ant}^{\log-per}$).

It can be observed that at 1.1THz a maximum in the emitted power with the meander antenna emitter is obtained (0.26 μW). If we compared both power measurements (meander and log-per antenna emitter) the plot in Fig. 7 is obtained. A small shift from 1.05 THz to 1.1THz can be appreciated but the power improvement is more or less the same (6 dB). In addition, the simulated quality factor (Q-factor) is 18.33, while the measured one is 10.11. This Q-factor decrease is due to the fact that additional losses not contemplated in the simulations such as losses in the silicon dielectric are occurring.

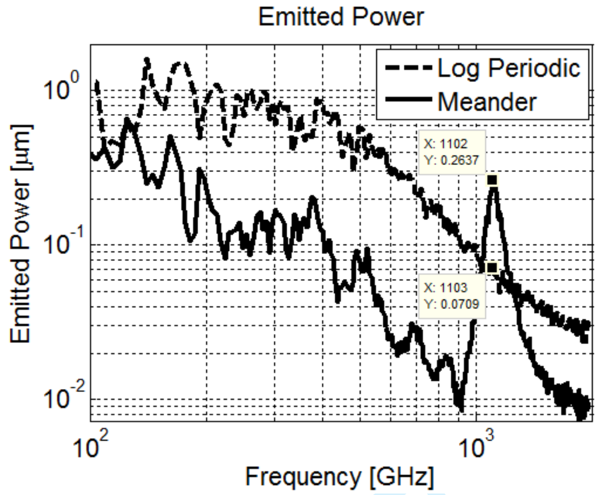


Fig. 8. Measured THz emitted power of both antenna emitters: meander dipole antenna and log-periodic antenna.

V. Conclusions

Meander dipole antenna has been presented as a solution to match both capacitive susceptance and conductance of photomixers while maintaining a relatively high value of radiation efficiency. To achieve such goal, we force the antenna to work out of its main resonance, at lower frequencies, where it exhibits an inductive behaviour.

With this approach, there is no need to include a RF choke, so the design of an antenna for CW THz based on photomixing is simplify to just the design of the meander dipole antenna. A joint design process of the antenna is proposed where both matching and radiation efficiencies (AIA concept) are taken into account. The proposed antenna design can be followed independently of the photomixer used and it consists on trying to maximize the radiated power obtained from it.

A prototype working at 1.05 THz was designed, manufactured and measured, and obtained results show a 6 dB improvement in THz output power when compared with the log-periodic prototype. This result is comparable with previously reported ones [11] at 1THz but with the novelty of not using the RF choke.

References

[1] P.H. Siegel, "Terahertz technology," *Microwave Theory and Techniques, IEEE Transactions on* , vol. 50, no.3 , pp. 910-928, March 2002

[2] G. Davies and E. Linfield, "Special Supplement: Terahertz Technology", *IET Electronic Letters*, December 2010.

[3] A. Rivera-Lavado, L. E. García-Muñoz, G. Dohler, S. Malzer, S. Preu, *et al*. "Arrays and New Antenna Topologies for Increasing THz Power Generation Using Photomixers", *Journal of Infrared, Millimeter, and Terahertz Waves*, Volume 34, Issue 2, pp 97-108, February 2013.

[4] J. C. Pearson, B. J. Drouin, A. Maestrini, I. Mehdi, J. Ward, *et al*, "Demonstration of a room temperature 2.48–2.75 THz coherent spectroscopy source," *Review of Scientific Instruments*, vol. 82, no. 9, p. 093105, September 2011.

[5] S. Preu, G.H. Döhler, S. Malzer, L.J. Wang, H. Lu, and A.C. Gossard, “Tunable, Continuous Wave Terahertz Photomixer Sources and Applications” (review article), *Journal of Applied Physics* 109, 061301-1-56, 2011.

[6] H. W. Hübers, S. G. Pavlov, A. D. Semenov, R. Köhler, L. Mahler, *et al*, "Terahertz quantum cascade laser as local oscillator in a heterodyne receiver," *Opt. Express*, vol. 13, no. 15, pp. 5890-5896, 2005.

[7] B. S. Williams, “Terahertz quantum-cascade lasers”, *Nature Photonics*, vol 1, pp. 517-525, September 2007.

[8] G.H. Dohler, L.E. Garcia-Munoz, S. Preu, S. Malzer, S. Bauerschmidt, *et al*, "From Arrays of THz Antennas to Large-Area Emitters," *Terahertz Science and Technology, IEEE Transactions on*, vol. 3, no. 5, pp. 532-544, September 2013.

[9] D. B. Rutledge, D. P. Neikirk, and D. P. Kasilingam, “Integrated circuit antennas,” Infrared and Millimeter Waves. New York: Academic, 1983, vol. 10, pp. 1–90.

[10] I.C. Mayorga, A. Schmitz, T. Klein, C. Leinz, R. Gusten, , "First In-Field Application of a Full Photonic Local Oscillator to Terahertz Astronomy," *Terahertz Science and Technology, IEEE Transactions on*, vol. 2, no. 4, pp. 393-399, July 2012.

[11] S.M. Duffy, S. Verghese, K. A. McIntosh, A. Jackson, A.C. Gossard, S. Matsuura, "Accurate modeling of dual dipole and slot elements used with photomixers for coherent terahertz output power," *Microwave Theory and Techniques, IEEE Transactions on* , vol. 49, no. 6, pp. 1032-1038, June 2001.

[12] T. Nguyen, and I. Park. "Resonant antennas on semi-infinite and lens substrates at terahertz frequency." *Convergence of Terahertz Sciences in Biomedical Systems*, Springer Netherlands, pp. 181-193, 2012.

[13] T. Endo, Y. Sunahara, S. Satoh, and T. Katagi, "Resonant Frequency and Radiation Efficiency of Meander Line Antennas", *Electronic Communications in Japan (Part 2)*, Vol. 83, No. 1, pp. 52-58, 2000.

[14] K. Chang, R. A. York, P. S. Hall, and T. Itoh, "Active Integrated Antennas", *IEEE Trans. Microwave Theory and Techniques*, Vol. 50, No. 3, pp. 937-944, 2002.

[15] D. Segovia-Vargas, D. Castro-Galán, L. E. García-Muñoz, and V. González-Posadas, "Broadband Active Receiving Patch with Resistive Equalization", *IEEE Trans. Microwave Theory and Techniques*, Vol. 56, No. 1, pp. 56-64, 2008.

[16] J. Montero-de-Paz, I. Oprea, V. Rymanov, S. Babiel, L. E. García-Muñoz, *et al*, "Compact Modules for Wireless Communication Systems in the E-Band (71–76 GHz)", *Journal of Infrared, Millimeter, and Terahertz Waves*, Volume 34, Issue 3-4, pp 251-266, April 2013.

[17] R. E. Collin, *Foundations for microwave engineering*, Wiley. com, 2007.

[18] C. Balanis, *Antenna Theory. Analysis and Design*, 2nd Edition, John Wiley & Sons, 1997.

[19] K. Moon, H. Han, and I. Park, “Terahertz folded half-wavelength dipole antenna for high output power,” *International Topical Meeting on Microwave Photonics (MWP 2005)*, 2005.

[20] H.C. Ryu, S.I. Kim, M.H. Kwak, K.Y. Kang, and S.O. Park, “A folded dipole antenna having extremely high input impedance for continuous-wave terahertz power enhancement,” *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2008.

[21] K. Baaskea, K. Ezdia, C. Jördensa, O. Petersa, M. Mikulicsb and M. Koch, “Folded dipole antenna for increased CW THz output power,” *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2009.

[22] H. Tanoto, J. H. Teng, Q. Y. Wu, M. Sun, Z. N. Chen, S. A. Maier, B. Wang, C. C. Chum, G. Y. Si, A. J. Danner and S. J. Chua, "Greatly enhanced continuous-wave terahertz emission by nano-electrodes in a photoconductive photomixer," *Nature Photonics*, Vol. 6, pp. 121-126, 2012.

Meander Dipole Antenna to Increase CW THz Photomixing Emitted Power

Javier Montero-de-Paz, Eduardo Ugarte-Muñoz,
Luis Enrique García-Muñoz, Iván Cámara Mayorga,
Daniel Segovia-Vargas, *Member, IEEE*

***Abstract*—The success in conquering the Terahertz (THz) gap is subject to some facts such as maximizing the emitted power. Traditionally resonant antenna designs for Continuous-Wave (CW) THz photomixing include a RF choke to compensate the capacitive part of the photomixer and an antenna with a very high input impedance at its resonance to match the low value of the photomixer conductance. This paper considers that the antenna itself can provide this large impedance margin needed to directly match the photomixer, so that the RF choke can be avoided. The meander antenna constitutes an excellent candidate to achieve that goal based on the Active Integrated Antenna concept to improve both matching and radiation efficiencies. The main objective is to maximize the total efficiency and, as a consequence, the THz emitted power. A prototype working at 1.05 THz is designed and manufactured and results show a 6 dB output power improvement when compared with a conventional log-periodic antenna.**

***Index Terms*—Active Integrated Antenna, CW Photomixing, Meander Dipole Antenna, THz**

I. Introduction

MAXIMIZING THz emitted power is one of the hot topics in the electronic and photonic communities nowadays [1], [2]. THz waves have been presented as one of the most promising research lines due to its unique capabilities. Extremely short pulses, capable of obtaining high spatial resolutions, going across light opaque materials and visualizing and identifying microscopic structures by spectral analysis, can be generated. Theoretically THz waves can find a lot of applications that range from radioastronomy, to imaging, security, biomedical, industrial, etc [1]. However, the low power that current devices can generate at these frequencies is the main drawback that these applications are finding to be developed. The power increase at THz frequencies in room temperature is then a key issue [3].

Two main approaches are being followed to generate THz waves at room temperature [1]. The first one is a purely electronic approach based on up-conversion [4] while the second one consists on an electro-optical down-conversion ("photomixing" [5]). In addition, direct quantum mechanical frequency generation (QCLs [6]) is a well established THz source. Unfortunately, nowadays it cannot work at room temperature [7]. Another interesting approach to generate THz CW power is the Large Area Emitter (LAE) concept [8]. This is an antenna-free new scheme of photomixing where the THz radiation is directly originated from the acceleration of photo-induced charge carriers generated within a large semiconductor area.

Photomixing is nowadays one of the most commonly used systems to generate CW THz signals due to its broadband nature and its reasonably high output power. It consists of two lasers working at two different frequencies ω_1 and ω_2 which are spatially overlapped to generate a THz beatnote. These lasers are then used to illuminate an ultrafast semi-conductor material (III-V family) such as GaAs. An applied electric field allows the conductivity variation to be converted into a current which is radiated by an antenna. The frequency of this current is the difference between both laser frequencies ($\omega_{THz} = \omega_1 - \omega_2$). A typical CW THz photomixing emitter consists on a semiconductor device (photomixer), a planar antenna (broadband or resonant one depending on the application) and a silicon hyper-hemispherical lens to increase the directivity and avoid substrate reflections [9]. Traditionally, photomixing is used in broadband applications such as spectrometry because of its high frequency tunability, so broadband antennas are preferred. However, it is also utilized as signal generator for LO on receivers [10]. In that case, a resonant antenna would be more suitable.

In [11], authors proposed a methodology to design resonant antennas to increase output power, which is the one that researchers designing THz photomixer based antenna emitters traditionally follow [10],[12]. Photomixers have a relatively high capacitive susceptance that is compensated with a RF choke. In addition, they exhibit a very low conductance value (typically lower than $(10k\Omega)^{-1}$), so a resonant antenna with a very high input impedance at its resonance would be desirable. With this approach, at least two components should be separately designed to be finally joined together: the RF choke and the antenna. Several attempts have been followed to design antennas with a very high value of its input impedance at its resonance [11],[12] to be included in CW THz photomixing devices. But all of them include the RF choke to compensate the capacitive susceptance, so the design of the overall structure is somehow complicated.

In this paper we propose for the first time in the THz gap the meander dipole antenna [13] as a solution to compensate both the capacitive susceptance and the conductance of the photomixer in a single element. The antenna design approach is based on the Active Integrated Antenna (AIA) concept [14], [15] to improve both the matching and the radiation efficiencies. The novelty of this work is that we forced the meander dipole antenna to work out of its main resonance, at lower frequencies, where it exhibits a clearly inductive behaviour. The proposed antenna design can be followed independently of the photomixer used and it consists on trying

Manuscript received 21, February, 2014. The work of J. Montero-de-Paz was supported by the Spanish Education Minister under the program FPU (AP2009-4679). The work of E. Ugarte-Muñoz was supported by the Spanish Economy Minister under the program FPI (BES2010-037676). This work was also supported by Consolider CSD 2008-00068.

J. Montero-de-Paz, E. Ugarte-Muñoz, L. E. García-Muñoz and D. Segovia-Vargas are with the Departamento de Teoría de la Señal y Comunicaciones, Universidad Carlos III de Madrid, Leganés, 28911 Spain (phone: +34 916246214; fax: +34 916248749; e-mail: jmontero@ tsc.uc3m.es, legarcia@tsc.uc3m.es, dani@tsc.uc3m.es).

I. Cámara Mayorga is with the Max-Planck-Insitut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany (e-mail: imayorga@mpifr-bonn.mpg.de)

to maximize the radiated power obtained from it. This same approach has also been followed in [16] with the design of a millimetre-wave Quasi-Optical Schottky Barrier Diode receiver. Unfortunately, the mismatch obtained with a broadband antenna in that case was not that huge, so little improvement was achieved.

The paper is organized as follows. After this brief introduction, the CW THz emitter structure is presented. The photomixer with its equivalent circuit and its main parameters will be shown. Next section will be devoted to describe the meander dipole antenna and its behaviour. Matching, radiation and total efficiencies will be calculated and a final design working at 1.05 THz will be presented and compared with a similar log-periodic based CW THz emitter. Finally, both meander dipole and log-periodic antenna emitters are manufactured to compare the performance of both of them.

II. CW THz Generation by Photomixing

As outlined in the introduction, in the traditional approach for CW THz generation by photomixing a THz current is generated in a semiconductor device using two heterodyned laser beams of photon energies $\hbar(\omega_0 \pm \omega_{THz}/2)$ (with the same power, $P_L/2$, and polarization), differing in photon frequency by the THz frequency ω_{THz} (being h the Planck constant and ω_0 the central frequency). As a first step, the heterodyned laser signal is absorbed on typical length scales shorter than 1 µm, i.e. much shorter than the THz wavelength. In the second step the resulting photocurrent is fed into an antenna, which then emits THz radiation [5]. A typical schematic of the CW THz generation by photomixing device, can be seen on Fig. 1.

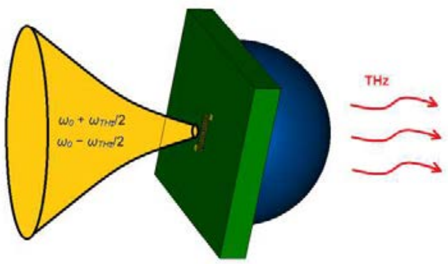


Fig. 1. Schematic of the CW THz photomixing antenna emitter. Two optical lasers impinge in the photomixer device which is integrated with an antenna over GaAs substrate (green part). A silicon lens (blue part) is included to avoid substrate reflections and increase directivity [9].

An interdigitated LT-GaAs based photomixer is used as the non-linear device to generate the THz signal. It consists of eight interdigitated fingers, with a finger gap = 1 µm, and finger width = 200 nm. Fig. 2(a) shows a SEM photograph of the device. The small-signal equivalent circuit of Fig. 2(b) [11] is obtained, being C = 2fF the parasitic capacitance from the fringing fields between the 200 nm wide fingers and $G = (10k\Omega)^{-1}$ the conductance given by I_{DC}/V_{DC}. The antenna admittance ($Y_a(\omega)$) is also included in the equivalent circuit of Fig. 2(b).

III. Meander Dipole Antenna Design

From the antenna point of view only two parameters can be optimized in order to maximize the THz emitted power: the radiation efficiency (ε_{rad}) and the mismatching factor (M). The mismatching factor is defined with the M-factor given by [17]:

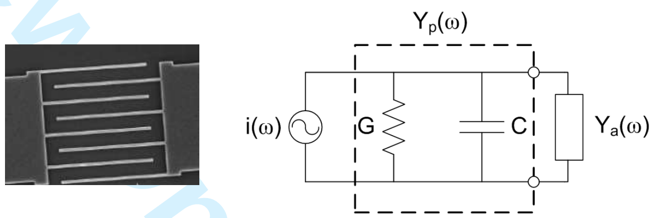
$$M = \frac{4R_a R_p}{\left(R_a + R_p\right)^2 + \left(X_a + X_p\right)^2} \qquad (1)$$

where $Z_a=R_a+jX_a$ is the input impedance of the antenna and $Z_p=R_p+jX_p$ is the input impedance of the photomixer.

The antenna efficiency can then be defined as the product of these two efficiencies and the polarization efficiency (ε_{pol}) [18]:

$$\varepsilon_{ant} = \varepsilon_{rad} \cdot M \cdot \varepsilon_{pol} \qquad (2)$$

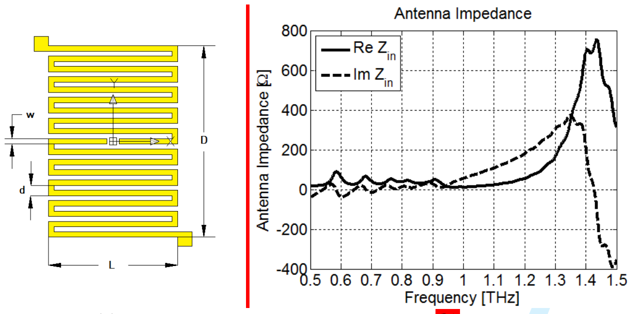
This efficiency expresses how far the system is from the ideal behaviour of the emitter. Maximizing this efficiency will enhance the performance of the emitter and it is the key factor that we have used to optimize the design of the antenna. This design is based on the AIA concept ([14],[15]) and tries to maximize the antenna efficiency as defined in Eqn. (2). In its design, both mismatching factor and radiation efficiency must be considered. With the photomixer parameters mentioned before, the input impedance ($Z_p(\omega)=1/Y_p(\omega)=1/(G+j\omega C)$, Fig. 2(b)) is found to be 0.57-j75.8 at 1.05 THz, so an antenna with an input impedance of 0.57+j75.8 at that frequency will maximize the Eqn. (1). This low value of the real part and relative high value of the imaginary part are very difficult to be simultaneously obtained with a simple resonant antenna.



(a) (b)

Fig. 2. (a) SEM photograph of the interdigitated LT-GaAs photomixer and (b) its equivalent circuit.

Meander dipole antenna is similar to a dipole where its radiating part is bent to a meander shape in order to reduce the antenna size [13]. A schematic of it with its main design parameters can be seen on Fig. 3(a). Traditionally, this antenna is used to reduce the antenna size (antenna miniaturization) and in systems that need a very high value of the input impedance, since this antenna provides higher values of input impedance at its resonance (Fig. 3(b)) than λ-dipoles or dual-dipoles [13]. In the THz region, this antenna has been used under the name of "folded dipole" to obtain a very high input impedance [19]-[22]. In all previous works, the antenna is working at its main resonance frequency (thus showing a high resistive input impedance). None of them try to maximize the M-factor and no attention is focused neither in the imaginary part of the input impedance nor the radiation efficiency. The novelty that we have pursued in the present work with the meander dipole antenna rises from using it out of its main resonance region [15], as at lower frequencies than its resonance it exhibits a low real part and an inductive behaviour (shown in Fig. 3(b), frequency range from 0.9 THz to 1.3 THz) suitable for matching it with the photomixer capacitive behaviour. With such design, we expect to achieve a conjugate matching between the antenna and the photomixer without any additional element, increasing the mismatching factor. The antenna will show the optimal input impedance to the photomixer, so an integrated active antenna is obtained [14]. According to [14] and [15], this design philosophy will improve the system parameters and the merit figure of the overall transmitter.



(a) (b)

Fig. 3. Meander dipole antenna: (a) Schematic and main parameters. (b) Simulated input impedance of a meandered dipole antenna over semi-infinite silicon substrate with parameters: L = 37 µm, w = 3.5 µm, d = 2 µm, D = 105.5 µm and 9 bends per arm.

A. Parametric study

In order to analyze the effect of each parameter on the antenna efficiency, several simulations have been done and results can be seen on Fig. 4 and Fig. 5. Full-wave electromagnetic simulator CST Microwave Studio has been used in order to carry out the simulations. Silicon semi-infinite substrate was set as background material in order to reduce computational time [12]. Both the mismatching factor and the radiation efficiency are shown, as well as the antenna efficiency (Eqn. (2), assuming $\varepsilon_{pol} = 1$).

The design parameters of the meander dipole antenna are (see Fig. 3(a)): the length (*L*), the width (*w*) of the arms, the separation between them (*d*) and the number of bends. Some conclusions can be extracted from these simulations. *L* parameter changes the resonant frequency of the meander antenna: the higher the value of *L* the lower the resonant frequency (larger size of the antenna). In addition, the closer the lines of the meander dipole antenna (lower value of *d*), the lower the radiation efficiency. This is due to the fact that currents have opposite directions so they cancel each other [13]. It is important to keep enough space between lines in order to have a relatively high value of the radiation efficiency. Regarding the number of bends, it has been noticed that for a number of bends higher than 3 (total length of the dipole > 2λ), neither the input impedance nor the radiation efficiency change significantly. Finally, *w* does not have an important role in both efficiencies and can be kept constant on optimization.

It is important to highlight that radiation efficiency keeps a relatively high value up to frequencies lower than 2/3 of its main resonance frequency. In all the above simulations, main resonance is located somewhere close to 1.5 THz (see Fig. 3(b)) and our design frequency is 1.05THz.

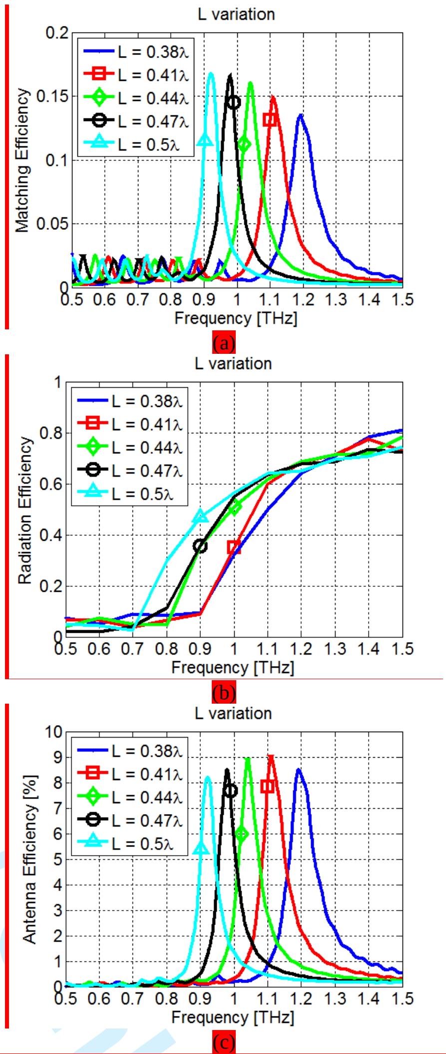


Fig. 4. L variation. (a) Matching efficiency, (b) radiation efficiency and (c) antenna efficiency. w = 0.044λ, d = 0.08λ.

IV. 1.05 THz PROTOTYPE

Finally, a prototype working at 1.05 THz as a LO for a radioastronomy heterodyne detector [10] was designed and manufactured. The main parameters are *L* = 37 µm, *w* = 3.5 µm, *d* = 2 µm, *D* = 105.5 µm and 9 bends per arm (Fig. 6). Separation between the middle arm and the following next (up or down) was fixed to 3.5 µm to keep enough space for the photomixer device. Simulated input impedance can be seen on Fig. 3(b). With such antenna an antenna efficiency of 7.05% at 1.05 THz is estimated, with matching and radiation efficiencies equal to 14.73% and 47.83% respectively. For the sake of comparison, a self-complementary log-periodic antenna [18] was designed and its antenna efficiency calculated. Its maximum and minimum dimensions are 200 µm and 10 µm respectively. In contrast with the meander dipole design, broadband antennas exhibit an almost constant impedance with frequency (self-complementary antennas: $60\pi/\sqrt{\varepsilon_r}$ for the real part and 0 for the imaginary part [17]), so little improvement can be achieved in the matching efficiency. In this second antenna emitter, an antenna efficiency of 1.73% is estimated with matching efficiency equal to 2.01% and radiation efficiency equal to 86.03%. Fig. 7 shows the simulated power improvement obtained with the meander dipole antenna emitter given by $\varepsilon_{ant}^{meander} / \varepsilon_{ant}^{\log-per}$. A 6 dB improvement at 1.05 THz is expected with the meander dipole antenna.

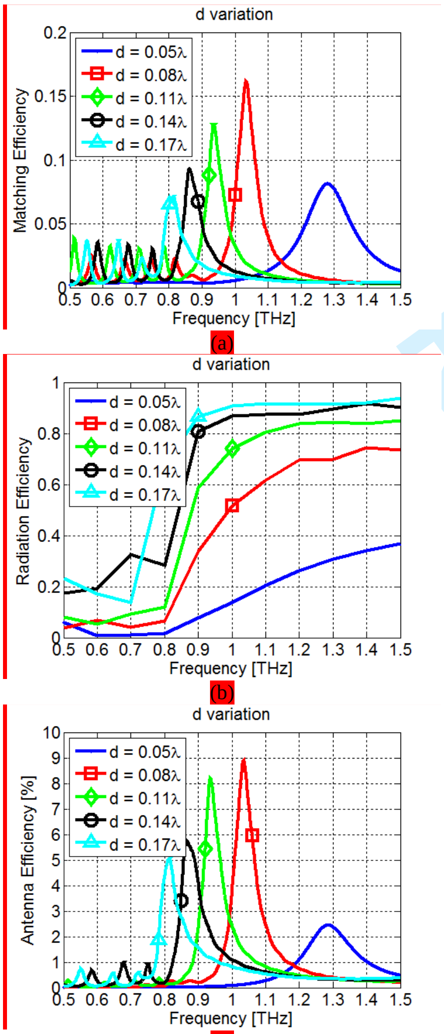
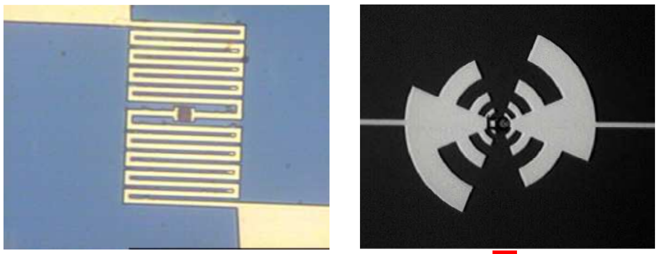


Fig. 5. *d* variation. (a) Matching efficiency, (b) radiation efficiency and (c) antenna efficiency. w = 0.044λ, L = 0.44λ.

Two antenna emitters, one with the meander dipole antenna and other with the log-periodic antenna were manufactured. In both of them, the same photomixer structure (Section II) and the same lens (10 mm diameter hyperhemispherical high resistivity silicon lens) were used. It is worth to highlight that the main challenge with the meander dipole antenna is that it is a highly resonant antenna, so a small variation in the manufacturing process or in the permittivity of the material would change its performance.



(a) (b)

Fig. 6. Photograph of the manufactured antennas integrated with the LT-GaAs photomixer device. (a) Meander dipole antenna and (b) Log-Periodic antenna.

A typical CW THz photomixing measurements setup was utilized to characterize the emitted power. It consists of two 850 nm lasers that illuminate the photomixer device. THz frequency is tuned and THz emitted power is measured from 80 GHz up to 2 THz. The photomixer output THz frequency depends on the frequency of the two lasers impinging over it. In the measurements shown in Figure 8, the frequency of one of the lasers remains constant while the other is changed to obtain the desired output THz frequency. This frequency change can be done either by modifying the current or the temperature of the laser. The THz radiation emitted by the antenna with the lens is, first, chopped with an optical chopper and then beam focused with two parabolic mirrors. The THz signal impinges a diamond window Golay cell connected to a lock-in amplifier which uses as the reference signal the chopper one. Measured output power with both meander and log-periodic antenna emitters are shown in Fig. 8.

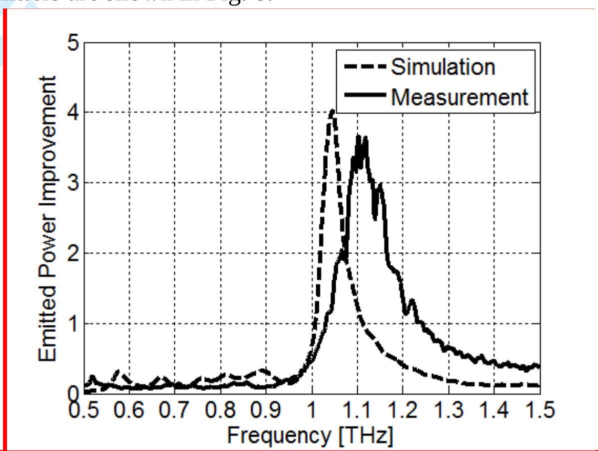


Fig. 7. Emitted power improvement when comparing meander dipole antenna with log-periodic antenna ($\varepsilon_{ant}^{meander} / \varepsilon_{ant}^{\log-per}$).

It can be observed that at 1.1THz a maximum in the emitted power with the meander antenna emitter is obtained (0.26 μW). If we compared both power measurements (meander and log-per antenna emitter) the plot in Fig. 7 is obtained. A small shift from 1.05 THz to 1.1THz can be appreciated but the power improvement is more or less the same (6 dB). In addition, the simulated quality factor (Q-factor) is 18.33, while the measured one is 10.11. This Q-factor decrease is due to the fact that additional losses not contemplated in the simulations such as losses in the silicon dielectric are occurring.

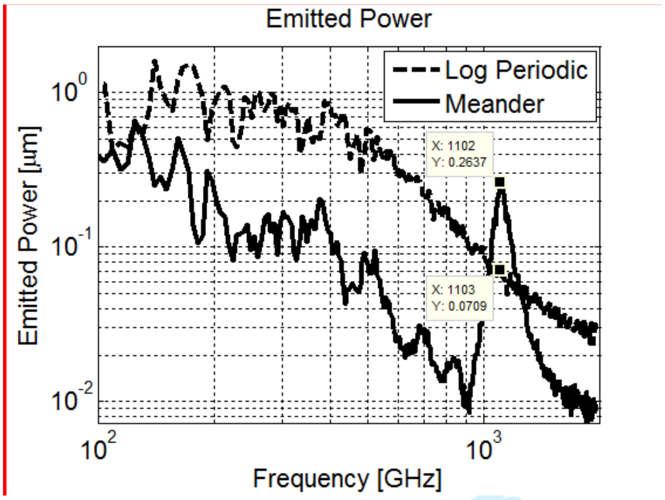


Fig. 8. Measured THz emitted power of both antenna emitters: meander dipole antenna and log-periodic antenna.

V. Conclusions

Meander dipole antenna has been presented as a solution to match both capacitive susceptance and conductance of photomixers while maintaining a relatively high value of radiation efficiency. To achieve such goal, we force the antenna to work out of its main resonance, at lower frequencies, where it exhibits an inductive behaviour.

With this approach, there is no need to include a RF choke, so the design of an antenna for CW THz based on photomixing is simplify to just the design of the meander dipole antenna. A joint design process of the antenna is proposed where both matching and radiation efficiencies (AIA concept) are taken into account. The proposed antenna design can be followed independently of the photomixer used and it consists on trying to maximize the radiated power obtained from it.

A prototype working at 1.05 THz was designed, manufactured and measured, and obtained results show a 6 dB improvement in THz output power when compared with the log-periodic prototype. This result is comparable with previously reported ones [11] at 1THz but with the novelty of not using the RF choke.

References

[1] P.H. Siegel, "Terahertz technology," *Microwave Theory and Techniques, IEEE Transactions on* , vol. 50, no.3 , pp. 910-928, March 2002

[2] G. Davies and E. Linfield, "Special Supplement: Terahertz Technology", *IET Electronic Letters*, December 2010.

[3] A. Rivera-Lavado, L. E. García-Muñoz, G. Dohler, S. Malzer, S. Preu, *et al*. "Arrays and New Antenna Topologies for Increasing THz Power Generation Using Photomixers", *Journal of Infrared, Millimeter, and Terahertz Waves*, Volume 34, Issue 2, pp 97-108, February 2013.

[4] J. C. Pearson, B. J. Drouin, A. Maestrini, I. Mehdi, J. Ward, *et al*, "Demonstration of a room temperature 2.48–2.75 THz coherent spectroscopy source," *Review of Scientific Instruments*, vol. 82, no. 9, p. 093105, September 2011.

[5] S. Preu, G.H. Döhler, S. Malzer, L.J. Wang, H. Lu, and A.C. Gossard, "Tunable, Continuous Wave Terahertz Photomixer Sources and Applications" (review article), *Journal of Applied Physics* 109, 061301-1-56, 2011.

[6] H. W. Hübers, S. G. Pavlov, A. D. Semenov, R. Köhler, L. Mahler, *et al*, "Terahertz quantum cascade laser as local oscillator in a heterodyne receiver," *Opt. Express*, vol. 13, no. 15, pp. 5890-5896, 2005.

[7] B. S. Williams, "Terahertz quantum-cascade lasers", *Nature Photonics*, vol 1, pp. 517-525, September 2007.

[8] G.H. Dohler, L.E. Garcia-Munoz, S. Preu, S. Malzer, S. Bauerschmidt, *et al*, "From Arrays of THz Antennas to Large-Area Emitters," *Terahertz Science and Technology, IEEE Transactions on*, vol. 3, no. 5, pp. 532-544, September 2013.

[9] D. B. Rutledge, D. P. Neikirk, and D. P. Kasilingam, "Integrated circuit antennas," Infrared and Millimeter Waves. New York: Academic, 1983, vol. 10, pp. 1–90.

[10] I.C. Mayorga, A. Schmitz, T. Klein, C. Leinz, R. Gusten, , "First In-Field Application of a Full Photonic Local Oscillator to Terahertz Astronomy," *Terahertz Science and Technology, IEEE Transactions on*, vol. 2, no. 4, pp. 393-399, July 2012.

[11] S.M. Duffy, S. Verghese, K. A. McIntosh, A. Jackson, A.C. Gossard, S. Matsuura, "Accurate modeling of dual dipole and slot elements used with photomixers for coherent terahertz output power," *Microwave Theory and Techniques, IEEE Transactions on* , vol. 49, no. 6, pp. 1032-1038, June 2001.

[12] T. Nguyen, and I. Park. "Resonant antennas on semi-infinite and lens substrates at terahertz frequency." *Convergence of Terahertz Sciences in Biomedical Systems*, Springer Netherlands, pp. 181-193, 2012.

[13] T. Endo, Y. Sunahara, S. Satoh, and T. Katagi, "Resonant Frequency and Radiation Efficiency of Meander Line Antennas", *Electronic Communications in Japan (Part 2)*, Vol. 83, No. 1, pp. 52-58, 2000.

[14] K. Chang, R. A. York, P. S. Hall, and T. Itoh, "Active Integrated Antennas", *IEEE Trans. Microwave Theory and Techniques*, Vol. 50, No. 3, pp. 937-944, 2002.

[15] D. Segovia-Vargas, D. Castro-Galán, L. E. García-Muñoz, and V. González-Posadas, "Broadband Active Receiving Patch with Resistive Equalization", *IEEE Trans. Microwave Theory and Techniques*, Vol. 56, No. 1, pp. 56-64, 2008.

[16] J. Montero-de-Paz, I. Oprea, V. Rymanov, S. Babiel, L. E. García-Muñoz, *et al*, "Compact Modules for Wireless Communication Systems in the E-Band (71–76 GHz)", *Journal of Infrared, Millimeter, and Terahertz Waves*, Volume 34, Issue 3-4, pp 251-266, April 2013.

[17] R. E. Collin, *Foundations for microwave engineering*, Wiley. com, 2007.

[18] C. Balanis, *Antenna Theory. Analysis and Design*, 2nd Edition, John Wiley & Sons, 1997.

[19] K. Moon, H. Han, and I. Park, "Terahertz folded half-wavelength dipole antenna for high output power," *International Topical Meeting on Microwave Photonics (MWP 2005)*, 2005.

[20] H.C. Ryu, S.I. Kim, M.H. Kwak, K.Y. Kang, and S.O. Park, "A folded dipole antenna having extremely high input impedance for continuous-wave terahertz power enhancement," *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2008.

[21] K. Baaskea, K. Ezdia, C. Jördensa, O. Petersa, M. Mikulicsb and M. Koch, "Folded dipole antenna for increased CW THz output power," *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2009.

[22] H. Tanoto, J. H. Teng, Q. Y. Wu, M. Sun, Z. N. Chen, S. A. Maier, B. Wang, C. C. Chum, G. Y. Si, A. J. Danner and S. J. Chua, "Greatly enhanced continuous-wave terahertz emission by nano-electrodes in a photoconductive photomixer," *Nature Photonics*, Vol. 6, pp. 121-126, 2012.