Terahertz polarizing component on cyclo-olefin polymer

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Abstract—Wire-grid polarizers constitute a traditional component for the control of polarization in free-space devices that operate in a broad part of the electromagnetic spectrum. Here, we present an aluminium-based THz wire grid polarizer, fabricated on a sub-wavelength thin flexible and conformal foil of Zeonor polymer having a thickness of 40μm. The fabricated device, characterized by means of THz time-domain spectroscopy, exhibits a high extinction ratio between 30 and 45dB in the 0.3-2.1THz range. The insertion losses oscillate between 0 and 1.1dB and they stem almost exclusively from moderate Fabry-Perót reflections and it is engineered for vanishing at 2THz for operation with quantum cascade lasers.

The terahertz (THz) frequency range is under intense investigation due to its applications in cross-disciplinary fields, such as secure short-range communications, life-science, defence and security [1-8]. In this scenario, the development of new THz components able to manipulate the THz radiation is a primary issue. Several research groups have been working on the design and fabrication of such components, e.g. filters, beam splitters, phase shifters, and electromagnetic absorbers [9-17]. Analysing and controlling the polarization of waves is a key basic functionality and, by using different approaches, various THz polarizers have been so far developed [18-21]. In our previous work [22], we demonstrated an Al-based THz wire grid polarizer (WGP) on a cyclo-olefin polymer substrate with very low THz absorption losses and high mechanical flexibility, which was mainly optimised for controlling the polarization in the low THz range. Here, we extend our work and demonstrate operation at about 2.0THz by using a 40μm thick Zeonor foil . This targeted frequency falls in the range delivered by Quantum Cascade Lasers (QCL) [23]. The fabricated WGP possesses a high extinction ratio (ER) and extremely low insertion losses (IL). The latter are mainly influenced by the Fabry-Pérot effect but vanish at the targeted frequency, thus producing no undesired reflection towards the QCLs. In general, thanks to the very low THz absorption losses of the polymer and its good processability, it is possible to engineer the matching frequency by properly selecting the substrate thickness. The properties of the WGP depend on its pitch *p*, the width of the metallic stripes *w* and the fill factor (*F*), defined as the ratio between the stripe width and the pitch of the one-dimensional periodic lattice. Both the period and the fill factor influence the polarizer's extinction ratio; when the period increases, the latter decreases while increasing the fill factor results in higher extinction ratios at the expense of increased IL, as extensively investigated in our previous work [22]. The matching frequency is ruled by the polymer thickness and its refractive index and in the WGP it is found at a somewhat lower frequency than in the simple dielectric foil of equal thickness.

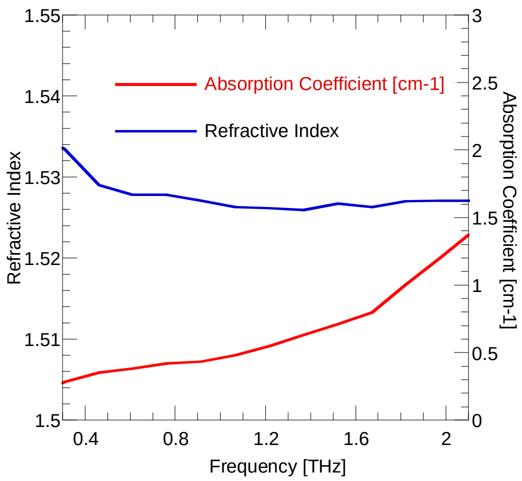

Fig. 1. Material properties of a 2-mm Zeonor sheet characterized by means of THz time-domain spectroscopy.

Before the fabrication process, a slab of 2mm thickness of Zeonor was characterized using THz time domain spectroscopy in order to validate the properties reported in the literature at the THz frequency range, as shown in Fig. *1*. The extracted refractive index is equal to 1.528 with minor dispersion in the spectral range under investigation while the absorption coefficient increases almost linearly from about 0 to 1.4cm^{-1} in the 0.6 to 2.1THz range, corresponding to an almost constant imaginary part of the refractive index of approximately 10^{-3} and a loss tangent of approximately $1.3{\cdot}10^{-3}$. Given the very low absorption, is has not been possible to

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characterize the 40 and 100µm Zeonor foils individually because the sample measurements are comparable to the oscillation of the THz signal. However, a stack of 100µm thick foils was assembled and measured as well. The material parameters are fully consistent with the accuracy in estimating the foils and slab thicknesses and with the values found in the literature [24].

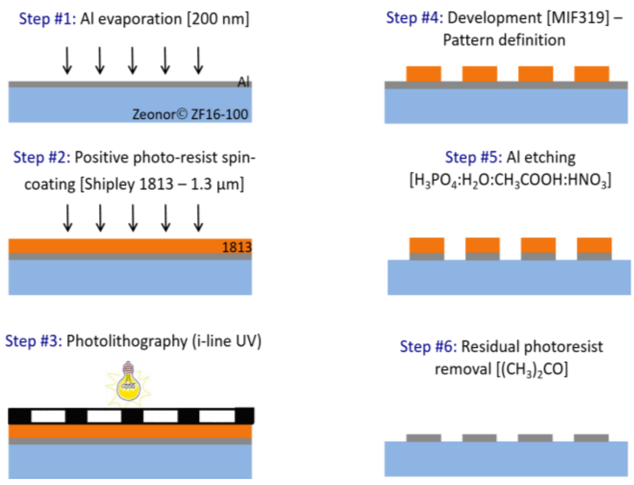

Fig. 2. Steps of the fabrication process of the investigated flexible THz-polarizers on Zeonor foils.

Two polarizers with a pitch 20µm and a fill factor of 70% (w=14µm) were fabricated on low loss flexible and conformal 40 and 100-µm-thick Zeonor foils sized 2.54cm ×2.54cm, using standard optical photolithography techniques. With respect to our previous work [22] we doubled the pitch to facilitate the fabrication of the THz-WGP on 40-µm-thick Zeonor foils. The fabrication flow is described in Fig. 2. At first, 200nm of aluminium were thermally evaporated on Zeonor foils. Subsequently, a film of the positive photoresist S1813 from Shipley was deposited using spin coating at 3000 rpm for 30 seconds, then backed at 115°C for 2 minutes. Its final thickness was 1.3±0.1µm. The photolithography is carried out on the top surface using a Karl Suss MA150 mask aligner with a wavelength of 365nm and intensity of 60mW/cm^2. The sample were immersed in the developer MF319 for 50 seconds, rinsed with deionized water, dried with nitrogen, and, afterwards, baked at 120°C for 5 minutes. Finally, the exposed aluminium was wet-etched in H_3PO_4:H_2O:CH_3COOH:HNO_3=16:2:1:1. Then the samples were cleaned with acetone and isopropanol. Fig. *3* illustrates the WGP fabricated on 40µm Zeonor thickness fixed on a standard 1” rotation mount while the inset reports a microphotograph taken under an optical microscope in transmission mode with a diffraction limited 100×/90 microscope objective, where the black parts are the Al stripes, while the transparent - Zeonor.

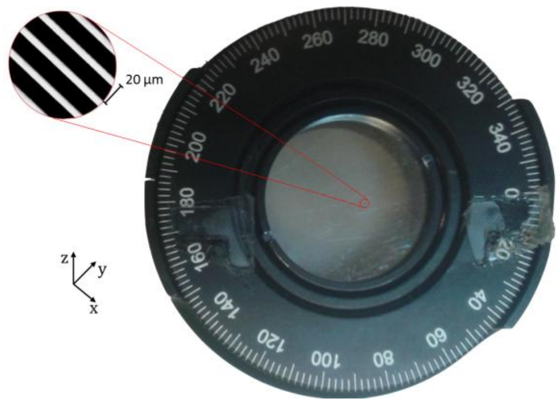

Fig. 3. Terahertz polarizer on a standard 1 inch mount. The inset reports a micrograph taken under the microspcope in transmission mode of a fabricated sample with p=20µm, w=14 µm on a Zeonor foil with d=40µm.

The electromagnetic properties of the WPGs were investigated by means of THz time domain spectroscopy using a Menlo Systems TERA K15 all fiber-coupled spectrometer in transmission mode. The measurements were done in an atmosphere purged with nitrogen in order to prevent water absorption of THz radiation. A detailed description of the measurement process is reported in our previous work [22].

Fig. *4* illustrates the comparison of numerical (solid lines) and experimental (markers) results of the power ER for THz WGPs with p=20µm and F=70% on Zeonor foil with a thickness (d) of 40 and 100µm. For both samples, the THz measurements agree very well with the simulations exhibiting an ER of 45 dB at 0.3THz which decreases as the frequency increases until the value of 30 dB at 2.1THz. It is interesting to note that the slope of the ER depends on the polymer thickness, in particular for the WGP fabricated on 40 µm Zeonor the slope is more regular with respect to the 100 µm one due to the Fabry-Pérot effects.

The influence of the polymer substrate on the polarizer performance is more evident in Fig. 5, which reports the comparison of experimental measurements (markers) and numerical (solid lines) results of the IL for the above samples. In fact, the WGPs exhibit two clearly different ILs that stay, however, between 0 and 1.1dB for both samples. Interestingly, owing to the matching condition, the WGP on a 40µm substrate possesses an IL of 0.18dB at around 2THz, which is difficult to achieve since most common polymers used at THz exhibit great attenuation at 2THz. Furthermore, the index matching condition is very important for use in combination with THz QCL sources because back-reflections are to be avoided [23].

Instead, the WGP on a 100µm foil shows the same trend observed in [22] where the IL approaches 0 dB at 0.9 and 1.7THz. It is worth noting that the matching frequency of the two devices does not simply scale with the thickness of the polymer foil. Here, we stress the fact that the matching frequency is shifted to lower frequency for a larger fill factor and for a larger pitch. Finally, we envisaged also the possibility of engineering the polarizers on thinner foils for operation at higher frequency where THZ QCLs deliver larger power, but we are currently limited by the dynamic range of the available instrument in estimating large extinction ratios.

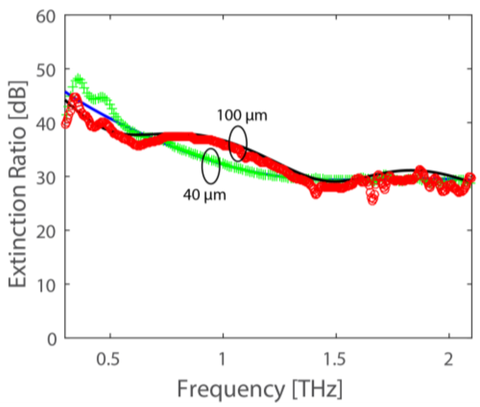

Fig. 4. Comparison of experimental measurements (markers) and numerical (solid lines) results of the extinction ratio for THz WGPs with p=20µm and F=70% on Zeonor foil 40 and 100µm thick.

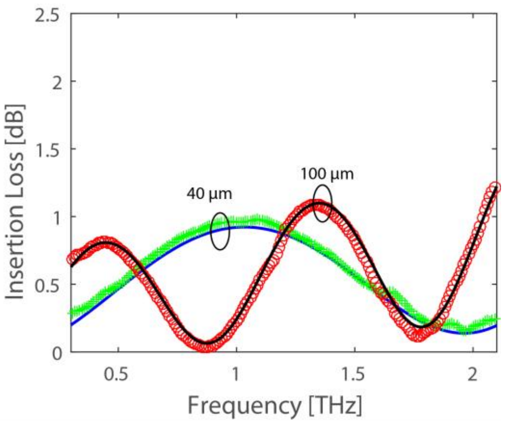

Fig. 5. Comparison of experimental measurements (markers) and numerical (solid lines) results of the insertion loss for THz WGPs with p=20µm and F=70% on Zeonor foil 40 and 100µm thick.

To sum up, in the present work we have demonstrated a rugged wire grid polarizer to be used with quantum cascade lasers. The investigated THz polarizers exhibit properties comparable to the commercial ones with ER and IL between 30 and 45dB and 0 and 1.1dB in the whole range under investigation. Moreover, the polarizers can be easily fabricated with low-cost techniques such as roll-to-roll and/or large-area electronics processes and promise to open the way for a new class of flexible and conformal THz devices.

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References

[1] I. F. Akyildiz, J. M. Jornet, C. Han, Phys. Commun. **12**, 16 (2014).
[2] M.C. Kemp, P.F. Taday, B.E. Cole, J.A. Cluff, A.J. Fitzgerald, W.R. Tribe, Proc. SPIE **5070**, 44 (2003).
[3] M. Schirmer, M. Fujio, M. Minami, J. Miura, T. Araki, T. Yasui, Biomed. Opt. Express **1**, 354 (2010).
[4] R.P. Cogdill, R.N. Forcht, Y. Shen, P.F. Taday, J.R. Creekmore, C.A .Anderson, J.K. Drennen, J. Pharm. Innov. **2**, 29 (2007).
[5] Y.-C. Shen, Int. J. Pharm. **417**, 48 (2011).
[6] A.G. Davies, A.D. Burnett, W. Fan, E.H. Linfield, J.E. Cunningham, Mater. Today **11**, 18 (2008).
[7] J.F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, D .Zimdars, Semicond. Sci. Technol. **20**, S266 (2005).
[8] D. Saeedkia, *Handbook of Terahertz Technology for Imaging, Sensing and Communications* (Elsevier, 2013).
[9] N. Born, M. Reuter, M. Koch, M. Scheller, Opt. Lett. **38**, 908 (2013).
[10] A. Ferraro, D.C. Zografopoulos, R. Caputo, R. Beccherelli, IEEE Photonics Technol. Lett. **28**, 2459 (2016).
[11] A. Ferraro, D.C. Zografopoulos, R. Caputo, R. Beccherelli, IEEE J. Sel. Top. Quantum Electron. 2017, DOI 10.1109/JSTQE.2017.2665641.
[12] B. S.-Y. Ung, B. Weng, R. Shepherd, D. Abbott, C. Fumeaux, Opt. Mater. Express **3**, 1242 (2013).
[13] J.-S. Li, D. Xu, J. Yao, Appl. Opt. **49**, 4494 (2010).
[14] K. Altmann, M. Reuter, K. Garbat, M. Koch, R. Dabrowski, I. Dierking, Opt. Express **21**, 12395 (2013).
[15] D.C. Zografopoulos, R. Beccherelli, Sci. Rep. **5**, 13137 (2015).
[16] G. Isić, B. Vasić, D. C. Zografopoulos, R. Beccherelli, R. Gajić, Phys. Rev. Appl. **3**, 064007 (2015).
[17] K. Iwaszczuk, A.C. Strikwerda, K. Fan, X. Zhang, R.D. Averitt, P.U. Jepsen, Opt. Express **20**, 635 (2012).
[18] F. Yan, C. Yu, H. Park, E.P.J. Parrott, E. Pickwell-MacPherson, J. Infrared Millim. Terahertz Waves **34**, 489 (2013).
[19] http://www.tydexoptics.com
[20] K. Imakita, T. Kamada, M. Fujii, K. Aoki, M. Mizuhata, S. Hayashi, Opt. Lett. **38**, 5067 (2013).
[21] A. Isozaki, et al., Solid-State Sens. Actuators Microsyst. Transducers Eurosensors XXVII 2013 Transducers Eurosensors XXVII 17th Int. Conf. On, IEEE, pp. 530–533 (2013).
[22] A. Ferraro, D. C. Zografopoulos, M. Missori, M. Peccianti, R. Caputo, R. Beccherelli, Opt. Lett. **41**, 2009 (2016).
[23] M.S. Vitiello, G. Scalari, B. Williams, P.D. Natale, Opt. Express **23**, 5167 (2015).
[24] A. Podzorov, G. Gallot, Appl. Opt. **47**, 3254 (2008).

