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Multibeam Transmitarrays for 5G Antenna Systems

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***Abstract*—In this paper, preliminary results on the feasibility of a multibeam antenna based on the use of a transmitarray are presented. A reduced size configuration has been properly designed and optimized, with the aim to minimize the degradation of the radiation pattern introduced by the variation in the direction of maximum radiation. Thereafter, the numerical analysis of the obtained antenna has been performed.**

***Index Terms*—Multibeam antenna, Transmitarray, MIMO antenna**

I. INTRODUCTION

The next 5th Generation (5G) of communication systems is expected to guarantee performances much higher than those provided by the previous standards: they will be able to serve a total amount of data that will increase by roughly 1000 times, with a worst data rate of 1 Gb/s, latency below 1 ms and reduced costs and energy consumption [1]. In order to satisfy all these requirements [2], a notable effort in the research and exploration of novel and revolutionary technologies is needed. In particular, the need of high data rates can be satisfied increasing the available frequency bands and the spectral efficiency. The first goal can be achieved moving towards higher frequencies (i.e. mm-waves) but also properly using the unlicensed bands in the μ-wave spectrum (e.g. those below 6 GHz). The higher spectral efficiency can be obtained with the use for base station antennas of massive Multiple-Input Multiple-Output (MIMO) architectures [3], [4]. Massive MIMO systems are characterized by a number of base station antennas larger than the served user terminals: in this way, it is possible to enhance the throughput capacity, keeping high the energy efficiency, reducing the latency and increasing the communication systems robustness against possible interferences.

The enabling technology for the realization of the base station radiating structures of a MIMO system is represented by multibeam antennas, able to radiate several independent, high gain beams covering different angular regions. A wide overview of the existing multibeam antenna technologies that could be adopted for the design of MIMO antennas is provided in [5]: both passive and active solutions are considered, ranging from phased arrays to configurations based on the use of reflector and proper feed-arrays. Among the others, also Transmitarrays (TAs) are considered as possible candidates for the realization of efficient multibeam antennas.

Transmitarrays represent one of the most promising solutions for the realization of high gain, low cost and high efficiency antennas [6]. A TA can be seen as a discrete version of a lens, where the curvature is simulated by a planar surface, divided in unit-cells with size equal or lower than half wavelength at the working frequency. In order to obtain the desired radiation pattern, the phase of the incident field is properly adjusted acting on one or more geometrical parameters of each unit-cell: it can consist of several layers of elements printed on dielectric substrates [7], perforated dielectric elements [8], or a combination of both techniques [9]. Moreover, the distance between the feed and the TA surface is generally optimized to reduce the spillover and enhance the gain. Transmitarrays can be adopted in a wide range of applications [6], and recently some results have also been presented on their use in massive MIMO systems [10].

In this paper, the possibility to realize multibeam TAs is investigated. Some results on this topic have already been published in [10]–[12]: they confirm that even locating the different feeds on the circular focal arc, there is a degradation of the beam introduced by the variation in the direction of maximum radiation. Here, an analysis of two different types of transmitarray unit-cells is carried on and possible solutions for an optimized design of a multibeam TA are presented. Preliminary results of their application to the design of a square TA, with an electrical size $D = 10\lambda_0$, being λ_0 the wavelength at the design frequency f_0, are discussed.

II. MULTIBEAM TRANSMITARRAY DESIGN

A multibeam Transmitarray consists in a planar surface, able to transform the incident field in a desired radiation pattern, and a feed-array, generating beams in different directions: they impinge on the TA surface with different angles of incidence and this affects the direction of maximum radiation of the entire antenna. A sketch of such a configuration is depicted in Fig. 1. When a TA is designed, each unit-cell is adjusted to compensate the phase of the incident field for a given frequency and a fixed position of the feed. When this last is moved, a defocusing effect occurs, and the radiation pattern of the entire antenna worsens: the main lobe becomes wider, the side-lobes increase and the gain decreases. These effects are mainly related to the behaviour of the unit-cell: the phase (and the amplitude) of the transmission coefficient S_{21} changes with the selected geometrical parameter(s) of the unit-cell, but also with the direction of arrival of the incident wave. As a consequence, when the incident field inpinges on the TA surface with an angle different from that considered for the antenna design, the unit-cells does not provide the required phase and the radiation pattern deteriorates.

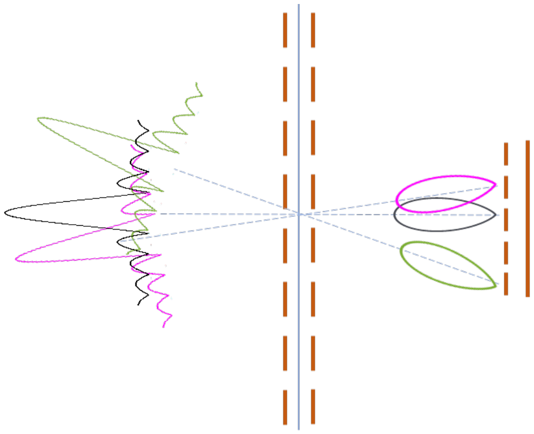

Fig. 1: Sketch of a multibeam transmitarray antenna

These considerations explain why the design of a multibeam transmitarray is still a challenging issue: overall, it involves the definition of both the TA planar surface and the feed-array. Here the focus is however on the first of these two elements and therefore the feed is simply modeled with a horn, whose position is changed along a circular focal arc. In fact, at this preliminary stage, the aim is to analyse which is the effect of the unit-cell on the radiation characteristics of the whole antenna and to present possible approaches for their provement.

A. The Unit-cell Analysis

Two different unit-cells are considered and compared to understand how their different characteristics impact on the features of a multibeam transmitarray. The first one, shown in the inset of Fig. 2, consists of three overlapping dielectric layers, with the same Malta-cross patch printed on each of them. The adopted material has a dielectric constant $\varepsilon_r = 2.57$ and a thickness $h = 0.5$ mm; the spacing between two following layers is equal to 13 mm, i.e. almost $\lambda_0/4$ at the design frequency $f_0 = 5.8$ GHz. The unit-cell size is $\lambda_0/2$.

In Fig. 2 the variation of the phase (top) and amplitude (bottom) of S_{21} with the width W of the Malta-cross for different angles of incidence is plotted. It is worth to notice that both the sets of curves are not continuous, and this is due to the fact that in correspondance of some values for W superior modes resonate, causing an abrupt discontinuity in the phase and a strong reduction in the amplitude of S_{21}: for this reason, these values have to be discarted. The selected range for W guarantees, at least for normal incidence ($\theta = 0°$), a phase variation of 370° and an amplitude not worse than -1 dB. Changing the angle of incidence, the value of S_{21} given by the same W varies, too: this means that when the feed is moved the unit-cell behaves in a different way and this could worsen the radiation features of the entire antenna.

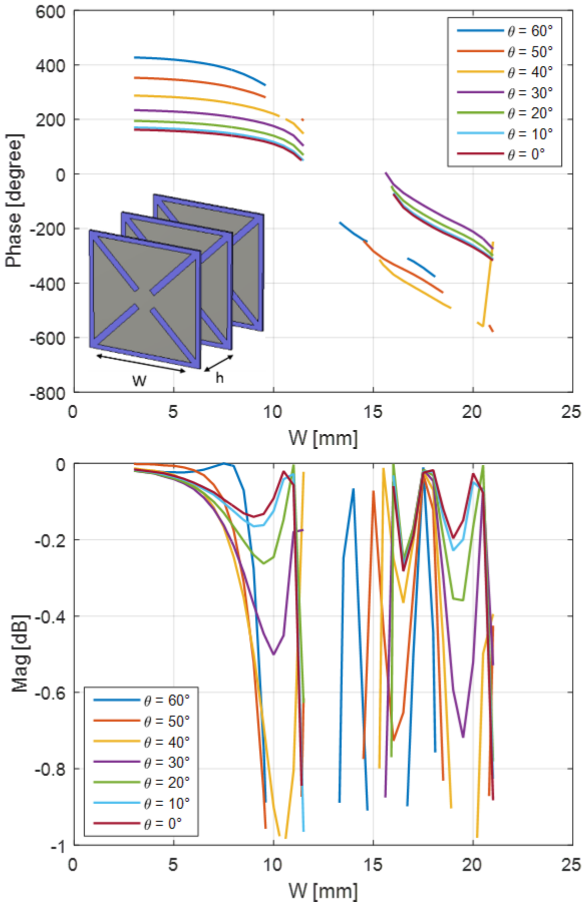

Fig. 2: Multi-layer Malta-cross unit-cell (inset). Variation of S_{21} with W for several angles of incidence. Top: phase. Bottom: amplitude.

The second considered type of unit-cell is a dielectric structure, made up of three layers: the central one presents a square hole, whose size W is varied to control the phase of S_{21}; the two identical external layers have a truncated pyramid hole, with smaller basis equal to W, and they act as matching circuits between the equivalent characteristic impedance of the central layer and that of the free-space [13]. The unit-cell has size equal to $\lambda_0/4$ and it is realized using the dielectric material Preperm L700HF, characterized by $\varepsilon_r = 7$ and tan$\delta = 0.001$. The adopted material has been selected since it can be used to manufacture the transmitarray with a 3D printing technique. The high value of the dielectric constant is favourable for reducing the thickness of the TA and therefore the losses it introduces: in the current case, the transmitarray total thickness is $1.38\lambda_0$.

The model of the unit-cell is shown in the inset of Fig. 3, where the variation of the phase (top) and amplitude (bottom) of S_{21} with W, computed for several angles of incidence, is plotted. The phase varies smoothly within a range of almost 550°; the curves corresponding to the different angles of incidence are almost parallel, and this behaviour indicates their weaker dependance from the direction of arrival of the impinging wave. This has however a stronger effect on the amplitude of S_{21}, that for increasing values of θ presents pronounced minima in correspondance of some size of the square hole.

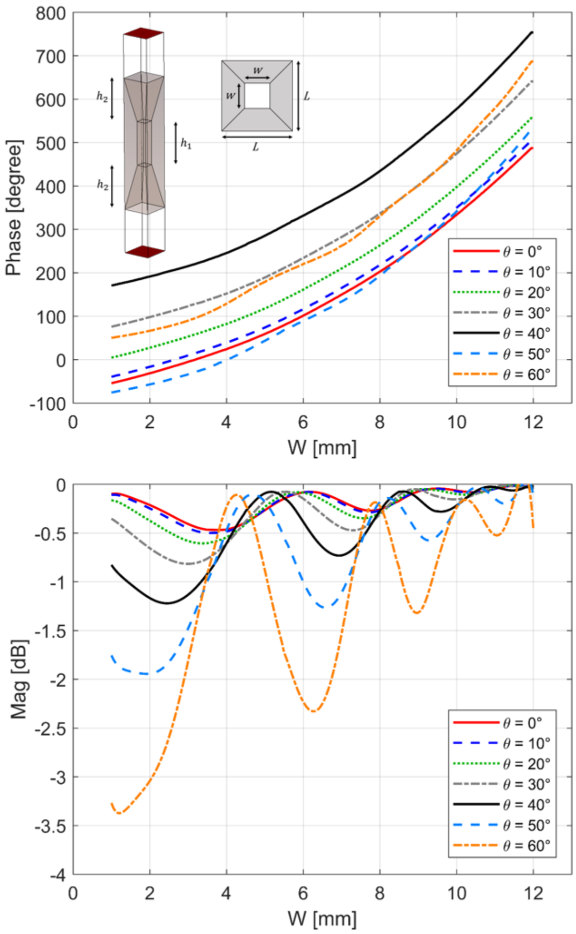

Fig. 3: Dielectric unit-cell (inset). Variation of S_{21} with W for several angles of incidence. Top: phase. Bottom: amplitude.

III. MULTIBEAM TA OPTIMIZATION

In view of the characteristics of the unit-cells described in the previous Section, two different possible techniques for obtaining different beams just moving the postion of the feed are here considered. In both cases, the size of the planar TA surface is assumed to be $10\lambda_0 \times 10\lambda_0$, while the ratio between the focal distance F and D is 0.9.

A. Bifocal TA Design

The dielectric unit-cell has shown lower dependence from the angle of incidence, and therefore it seems to be a good candidate for realizing an optimized multibeam TA acting as a bifocal lens [14]. In fact, it is proved that such a configuration focuses quite well when the incident wave is coming from one of the two focal points or in their proximity. According to what is done in [14] for the case of a reflectarray, the procedure for the design of a bifocal TA can be summarized in the following steps:

- Assume the feed located in an off-set position, with the main beam forming an angle θ_1 with the $z-$axis, orthogonal to the TA surface and compute the required phase distribution;
- Rotate the feed, so that it keeps the same distance from the TA surface, but the direction of maximum radiation now forms an angle θ_2 With the $z-$axis, and compute the new phase distribution;
- Since the unit-cells have just one degree of freedom, they are not able to provide concurrently the two desired phase distribution; for this reason, the TA is designed so that each element produces the mean value between the phases needed considering θ_1 and θ_2 as angles of incidence.

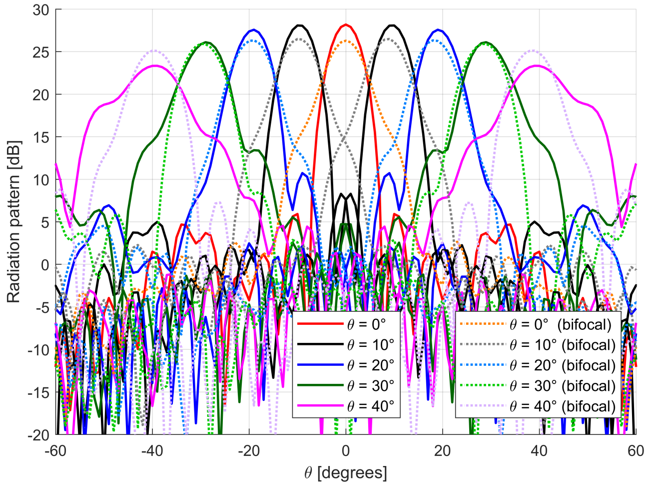

Fig. 4: Radiation pattern of dielectric TAs of different scanning angles. Dotted lines: bifocal design. Solid lines: conventional design.

Here maximum scannings of -40° and +40° would be achieved, and therefore these two angles are used as θ_1 and θ_2. Once the TA is designed applying the bifocal technique, its numerical analysis is performed and the radiation patterns for different angles of pointing are computed (Fig. 4, dotted lines). The solid curves instead represent the radiation patterns obtained when the TA is designed according to the conventional procedure. The comparison between the two set of curves proves that the bifocal TA has better scanning performances, even if at the cost of a reduction of the gain and a deterioration of the main beam in the broadside direction, that corresponds to have the feed in the farest position from the two adopted focal points. In any case, the gain decreases slower and also the side lobe level increases less.

The advantages of the bifocal design are improved by the features of the unit-cell; if in fact it is adopted in conjuction with the multi layer Malta-cross, the resulting radiation patterns are worst than those plotted in Fig. 4. Therefore, for this case, another method for the TA optimization is needed.

B. $M_Q C_{10} - BBO$ *based Optimization*

In order to further improve the performances of the design procedure of a multibeam transmitarray, another aprroach, based on the use of a global optimization algorithm, is investigated.

The selected optimization method is one of the modified Biogeography Based Optimization (BBO) schemes introduced in [15]. They are enhanced versions of the standard BBO [15], where the linear model used for the quantities that regulate the exchanging of features among solutions is substituted by a quadratic or a cosine one, and a further parameter, named cataclysm, is added to generate a new population when the algorithm stagnates. Among the different schemes, the most efficient turned out to be the $M_Q C_{10}$-BBO, i.e. that adopting the quadratic model and taking not less than 5×10 iterations between two following cataclysms [15], [16].

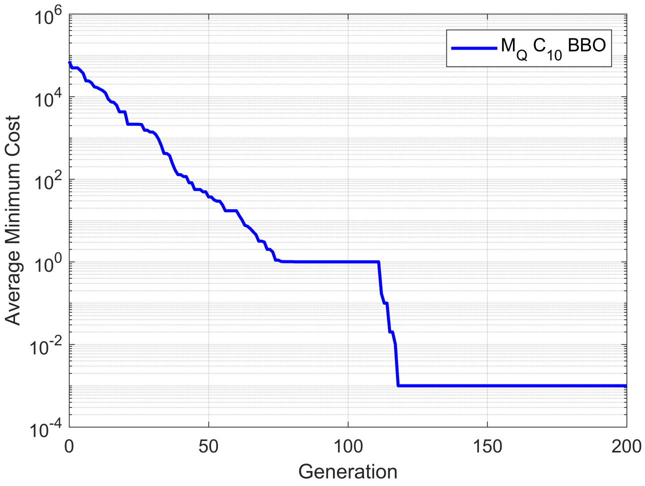

Fig. 5: Curve of convergence ofr the $M_Q C_{10}$-BBO when applied to the optimization of the multi-layer Malta-cross transmitarray.

The $M_Q C_{10}$-BBO scheme has been applied to optimize the radiation pattern of the multibeam transmitarray made up of 20×20 multi-layer Malta-cross patches. The phase of the radiated field of each array element is assumed to be a variable in the optimization process. Considering that the structure is symmetrical in both the x and y directions, the total number of the variables is equal to 100 (10×10). To optimize the radiation patterns, a set of shaped masks have been defined for some angles in the considered range: $\theta = -40°$, $\theta = -30°$, $\theta = -20°$, $\theta = -10°$ and $\theta = 0°$ for the E-plane and $\theta = 0°$ for the H-plane. The aim of the optimizer is to find the TA configuration that radiates a pattern satisfying all the masks. The cost function is written as summation of terms that allow to control the beam direction, the side lobe levels and the beam width, and it includes numerical weights and penalty functions, as done in [14] and [16]. The optimization has been carried out using a population of 200 elements, while the total number of iterations is 200. In Fig. 5, the curve of convergence for the average minimum cost is shown.

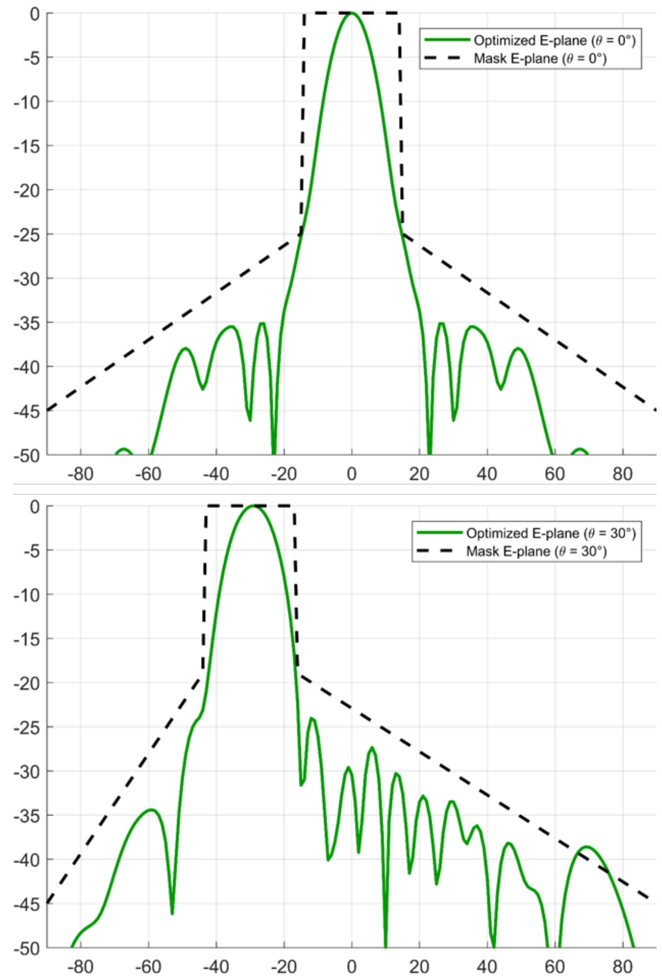

Fig. 6: Optimized radiation patterns (E-plane) for $\theta = 0°$, $\theta = -30°$ and related masks

In Fig. 6 the radiation patterns obtained by the optimizer for scanning angles equal to $\theta = 0°$ and $\theta = -30°$ are plotted, together with the corresponding masks. In both cases they are well satisfied, proving the possibility to improve the design of a multibeam TA using a proper optimization technique.

IV. CONCLUSION

In this paper, the feasibility of multibeam Transmitarray Antennas is proved. It is worth to note that the first method exploited here is useful and simple but it does not work well for all the structures. When a more complex unit cell is designed (i.e. Malta-cross) an optimization algorithm has to be used, and the results show that the $M_Q C_{10}$-BBO scheme has a very good application to this case, reducing the time of the design while providing efficient solutions.

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REFERENCES

- [1] J. G. Andrews, *et al.*, "What will 5G be?," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
- [2] E. Dahlman, *et al.*, "5G wireless access: Requirements and realization," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 42-47, Dec. 2014.
- [3] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.
- [4] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.
- [5] Wei Hong, *et al.*, "Multibeam Antenna Technologies for 5G Wireless Communications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6231–6249, Dec. 2017.
- [6] A. H. Abdelrahman, F. Yang, A. Z. Esherbeni, and P. Nayeri, *Analysis and Design of Transmitarray Antennas.*, M&C Publishers, 2017
- [7] C. G. M. Ryan, *et al.*, "A wideband transmitarray using dual-resonant double square rings," *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1486–1493, May 2010.
- [8] A.-E. Mahmoud, W. Hong, Y. Zhang, and A. Kishk, "W-band mutlilayer perforated dielectric substrate lens," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 734-737, 2014
- [9] W. An, S. Xu, F. Yang and M. Li, "A Double-Layer Transmitarray Antenna Using Malta Crosses With Vias," *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 1120–1125, March 2016.
- [10] M. Jiang, Z. N. Chen, Y. Zhang, W. Hong, and X. Xuan, "Metamaterial-based thin planar lens antenna for spatial beamforming and multibeam massive MIMO," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 464–472, Feb. 2017.
- [11] E. G. Plaza, J. R. Costa, C. A. Fernandes, G. Len, S. Loredo, and F. Las-Heras, "A multibeam antenna for imaging based on planar lenses," *9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, 2015, pp. 1–5.
- [12] Z. C. Tsai, and H. T. Chou, "Waveguide-type transmitarray antennas with a concave surface profile analogous to rotman lens for spatial feeding to radiate collinear multi-beams," *2017 International Symposium on Antennas and Propagation (ISAP)*, Phuket, 2017, pp. 1–2.
- [13] A. Massaccesi, P. Pirinoli, "Enhancing the Bandwidth in Transmitarray Antennas Using Tapered Transmission Line Matching Approach," *12th European conference on Antennas and propagation (EuCAP)*, London, UK, April 2018.
- [14] P. Nayeri, F. Yang, A. Z. Elsherbeni, "Bifocal design and aperture phase optimizations of reflectarray antennas for wide-angle beam scanning performances," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4588-4597, Sept. 2013.
- [15] M. Mussetta, P. Pirinoli, "$\mathrm{M}_m\mathrm{C}_n$-BBO schemes for electromagnetic problem optimization,"*7th European Conf. on Antennas and Propag. (EuCAP)*, Gothenburg, 2013, pp. 1058–1059.
- [16] P. Pirinoli, A. Massaccesi, and M. Beccaria, "MmCn-BBO schemes for electromagnetic problem optimization,"*2017 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Verona, 2017, pp. 1850-1854.