Discussions on the FSS Transmitted Beam Shift in Quasi-optic Instruments

M. Jin, **Y. Bai**, **and C. Gao**
Science and Technology on Electromagnetic Scattering Laboratory, Beijing 100854, China

Abstract— The Frequency Selective Surface is the key component in the Quasi-Optic instrument for feeding large reflector antennas, because of that beams from horns in different frequency band can be combined on a sharing feeding aperture. The aberration to the transmitted beam through FSS is an important problem in fabricating a multi-band QO feed, and must be evaluated in the design stage. Recently, an efficient anticipation method was reported, which can be used to predict the tangential beam shift caused by the FSS and one FSS design is considered. In this paper, we will further discuss the longitude transmitted beam shift anticipation, and consider another FSS structure to show that method can be universal to different FSS structural types.

1. INTRODUCTION

The Quasi-Optical (QO) and beam waveguide (BWG) instruments have found to be with high transmission efficiency and low dispersion, and have become popular in the reflector antenna systems [1–3]. The frequency selective surface (FSS) is the key component in the multi-band QO and BWG, as one can use it to combine beams in different frequency bands onto a shared feed aperture [4, 5]. To be more specifically, a beam in the stop band can be reflected by the FSS, while that in the pass band can be transmitted through it. For the transmitted beam, the FSS structure will introduces both degradation (beam deforming) and shifting effects, which bring difficulties in fabricating a multi-band QO or BWG instrument and must be evaluated [1–3, 6]. The degradation effect due to the FSS has been intensively studied. In most of the reports, methods based on plane-wave spectrum (PWS) formulations have been proposed and verified to be accurate in finding the transmitted field distributions [6–9]. In those methods, the incident and transmitted beams are expanded in the plane wave spectrum and the influence on each PW component by FSS can be included in the analysis. Consequently, results of a 2-D angular sweeping of simulations under periodic boundary conditions (PBC) are required to implement the PWS method [6–10].

In a multiband QO instrument, the FSS is deployed among a serial of components in each beam path, where systematic design has to be performed [1–4]. In this case, an even more efficient method to investigate the transmitted beam aberrations would help in the early design stage. Recently, we reported a anticipation method for the transmitted beam shift caused by FSS [11]. That method is based on the phase analysis of the plane-wave transmission functions of FSS within a range of incident angles, and only the results of a 1-D sweeping of PBC simulations is required. In the reported work, the anticipation method for tangential beam shift was validated by the PWS algorithms. In this work, we are to discuss the longitudinal transmitted beam shift, and address another FSS structure to show the university of that Method.

2. ANALYTIC MODEL AND VERFICATION METHOD

2.1. Analytic Model

In Fig. 1, the analytic model for anticipating the transmitted beam shift through FSS is presented, along with the beam transmission through free-space as the reference. The difference between the analytic model in this work and that in [11] is the consideration of longitudinal beam shift Δl. As the detailed derivations for the beam shift anticipation can be found in [11], related formulations would not be included in this paper for brevity. Further, the formulations related to the Δl which has not been included in [11] will be presented in this work.

In Fig. 1, the transmitted aperture TA is shifted from RA (reference aperture) with tangential beam shift of Δt and Δl, so that the transmitted beam on TA in the FSS transmitted system is most approximated to that on RA in the Free-space transmission system. Considering the plane wave transmission function in the Free-space system to be $h(\theta, \varphi)$, that in the FSS system from IA to TA to be $\arg(h^t_{\xi\xi}(\theta, \varphi, \Delta t, \Delta l)$, and that from IA to RA to be $h^{t0}_{\xi\xi}(\theta, \varphi)$. We have:

$$h^t_{\xi\xi}(\theta, \varphi, \Delta t, \Delta l) = h^{t0}_{\xi\xi}(\theta, \varphi) \cdot e^{-j\begin{bmatrix} (-\Delta t \cdot \cos\alpha + \Delta l \cdot \sin\alpha) \cdot k_x \\ +(\Delta t \cdot \sin\alpha + \Delta l \cdot \cos\alpha) \cdot k_z \end{bmatrix}} \tag{1}$$

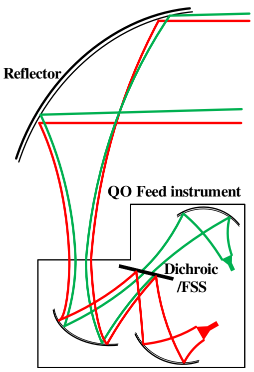
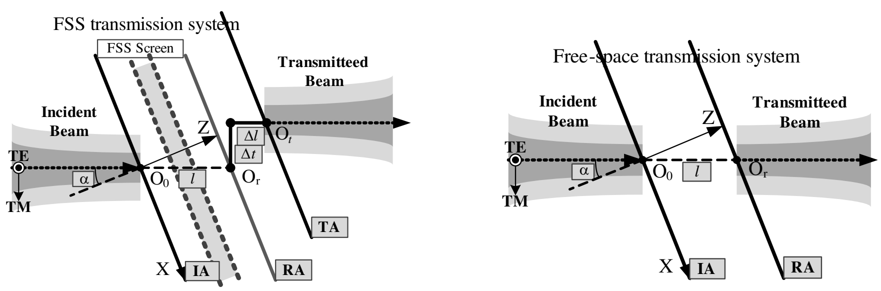


Figure 1: Configuration of an FSS in an QO feed for reflector antenna (not to scale), the beam shift effect by FSS is also demonstrated.

Actually, the beam shift cause by the FSS is due to the difference between the phase distributions of $h^{t0}_{\xi\xi}(\theta,\varphi)$ and $h(\theta,\varphi)$. If proper Δt and Δl can be introduced as in Fig. 2, so that $\arg(h^{t}_{\xi\xi}(\theta,\varphi,\Delta t,\Delta l)$ approximates to $\arg(h(\theta,\varphi)) + \mathbf{Cons}$, then the FSS transmitted system with corresponding Δt and Δl can be regarded as the shift-corrected one for beam transmission. Here, **Cons** stands for a constant number.



(a) (b)

Figure 2: Configuration of beam propagation systems with a FSS screen and without a FSS screen (Free-space).

We are to do the phase analysis in the XOZ plane. The first step is conducting an 1-D θ sweeping ($\varphi = 0°$) of PBC-simulations for the FSS structure, using commercial software [12] to obtain the $h^{t0}_{\xi\xi}(\theta, 0°)$. Then, a phase difference function is defined as:

$$p^d_{\xi}(\theta,\Delta t,\Delta l) = \arg(h(\theta,0°)) - \arg\left(h^{t}_{\xi\xi}\left(\theta,0°,\Delta t,\Delta l\right)\right) \tag{2}$$

Now we can perform the beam shift anticipation by doing:

(1) Tangential shift correction: Adjusting Δt to have $p^d(\theta,\Delta t,\Delta l = 0)$ reach its extremum at $\theta = \alpha$, that also means $\arg(h^{t}_{\xi\xi}(\theta,0°,\Delta t,0))$ reaches its extremum at $\theta = \alpha$ as $\arg(h(\theta,0°))$ does. The founded Δt is named as Δt_a.

(2) Longitudinal shift correction: Adjusting Δl to make the absolute value of $p^d(\theta,\Delta t_a,\Delta l)$ as small as possible within the region of θ we care. The founded Δl is called by Δl_a.

In this paper, the scheme to find Δt_a and Δl_a is called the ***Phase Correction*** scheme.

2.2. Verification Method

To validate the anticipated beam shift, Δt_a and Δl_a, a direct way is to compare the FSS transmitted fields on **TA** with the free-space transmitted fields on **RA**. The PWS method can be used in accurately finding the transmitted fields through FSS, as has been proven in a number of references [6–10]. The incident is the same as in [11]. For the TM or TE incident, we set the incident field distributions on **IA** to be with only E_x(E_z also exists but is not needed to be considered in the calculation) or E_y component respectively.

Further evaluation of the beam shift Δt and Δl basing on the PWS simulation results can be done via the coupling coefficients. The free-space transmitted fields on **RA** are considered as the reference, to be compared with the FSS transmitted fields on **TA** with Δt and Δl as variables. Then coupling coefficients $C(\Delta t,\ \Delta l)$, between the free-space transmitted fields E_ξ^{Free} and FSS transmitted fields $E_\xi^{FSS}(\Delta t, \Delta l)$, is defined as:

$$C^{POL}(\Delta t, \Delta l) = \left| \frac{\left\langle E_\xi^{Free} | E_\xi^{FSS}(\Delta t, \Delta l) \right\rangle}{\left\langle E_\xi^{Free} | E_\xi^{Free} \right\rangle^{0.5} \cdot \left\langle E_\xi^{FSS}(\Delta t, \Delta l) | E_\xi^{FSS}(\Delta t, \Delta l) \right\rangle^{0.5}} \right| \tag{3}$$

where: $\langle f|g\rangle = \iint f(x,y) \cdot g^*(x,y)dxdy$, and POL stands for TM or TE, when ξ stands for x or y respectively. Clearly, when $C(\Delta t, \Delta l)$ reaches its maximum value, the corresponding $\Delta t_{\max}$ and $\Delta l_{\max}$ is the correct shift compensation for $\mathbf{O}_t$ as in Fig. 2.

3. RESULTS AND DISCUSSIONS

First, the same FSS structure studied in [11] is considered in this work, which is design for TE and TM beam transmission around 90 GHz at oblique incident of ($\theta = \alpha = 30°$, $\varphi = 0°$). At 90 GHz, the $p^d(\theta)$ curves for TE and TM beam shift anticipation is presented in Fig. 4. Then those anticipated Δt_a and Δl_a are verified by the coupling coefficient results based on the PWS calculated field distributions, as in Fig. 5. As can be seen, the Δt_a can be accurately anticipated as stated in [11]. However, the anticipated Δl_a is near to but not at, the positions where the maximum of coupling coefficient $C(\Delta t_{\max},\ \Delta l)$ stand. This fact implies the information that $\arg(h_{\xi\xi}^t(\theta, 0°))$ offers is not sufficient for the accurate Δl determination. On the other hand, results shows that coupling coefficients $C(\Delta t, \Delta l)$ varies much more severely versus Δt than versus Δl. And this fact agrees with the common sense that the tangential beam shift Δt caused by FSS is much more

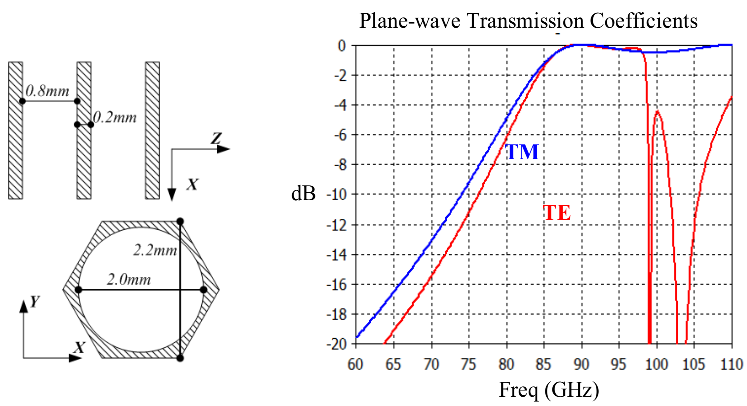


Figure 3: 3-layer FSS structure and its transmission coefficients at the design angle ($\theta = 30°$ and $\varphi = 0°$).

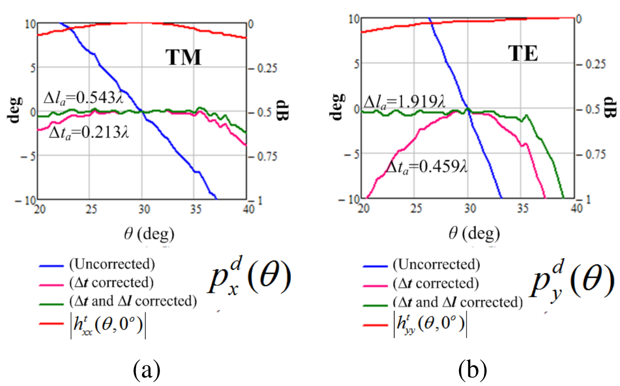


Figure 4: The $p^d(\theta)$ curves in different stages of phase correction scheme, at 90 GHz, in cases of (a) TM and (b) TE incident.

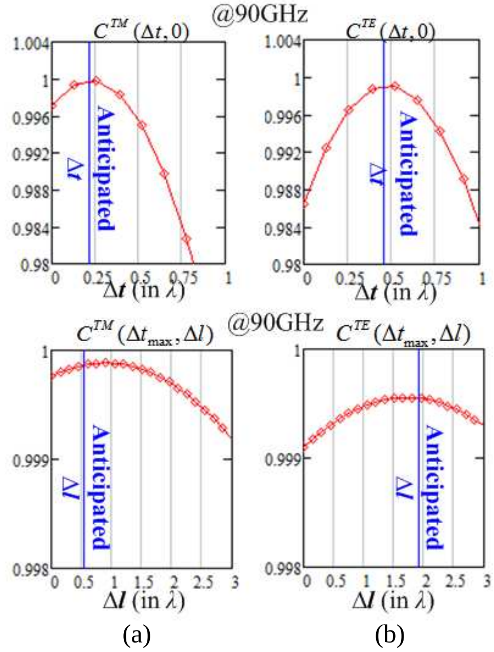


Figure 5: Curves of calculated coupling coefficients between Free-space transmitted fields on **RA** and FSS (the first one) transmitted fields on **TA** as in Fig. 2, along Δt (first row) and Δl (second row), at 90 GHz, in the cases of (a) TM and (b) TE incident; the positions of anticipated Δt_a and Δl_a by the proposed method are also marked.

worthy of attentions than the longitudinal shift Δl, for the sake of transmission efficiency in the design of an QO feed.

Another FSS design considered in this work, is a two-layer ring slot structure supported by a dielectric plate. The purpose to study such a FSS design is to show that the method can be utilized regardless of FSS structure types. The plane-wave transmission coefficients at the design angle ($\theta = \alpha = 30°$, $\varphi = 0°$) are shown in Fig. 6. The anticipated Δt_a from 85 GHz to 100 GHz by the phase correction scheme, and the corresponding $C^{TE}(\Delta t, \Delta l = 0)$ and $C^{TM}(\Delta t, \Delta l = 0)$ distributions based on the PWS simulation results, are presented in Fig. 7. In both the cases of TE and TM incident, the corresponding anticipated Δt_a walk along the maximum $C(\Delta t)$ positions which are near to $\Delta t = 0$, that means the tangential shift anticipations were accurate within the pass band. Meanwhile, the fact that the maximum of $C(\Delta t)$ approaches to 1 (> 0.999) from 85 GHz to 100 GHz in both the cases of TE and TM incident, shows that the degradation effects by the FSS are weak.

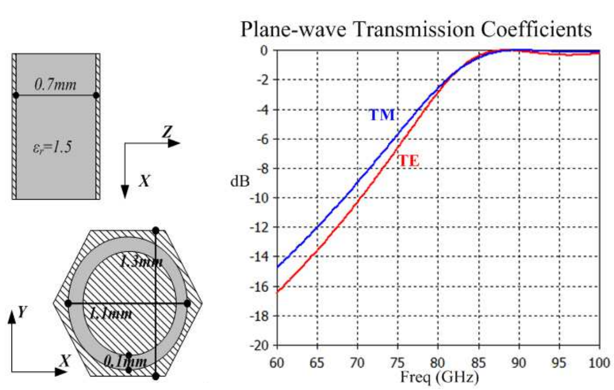


Figure 6: 2-layer FSS structure and its transmission coefficients at design angle ($\theta = 30°$ and $\varphi = 0°$).

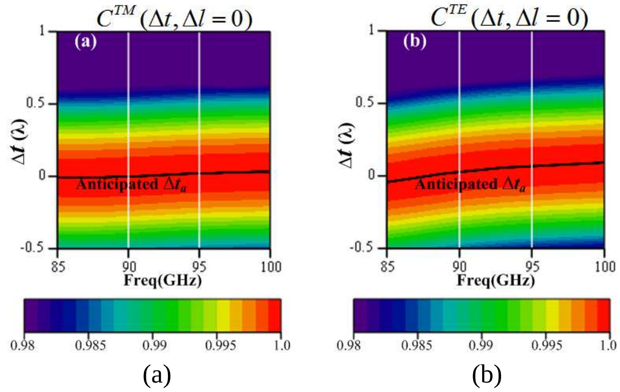


Figure 7: Distribution of calculated coupling coefficients $C(\Delta t, \Delta l = 0)$, between free-space transmitted fields on **RA** and FSS (the second one) transmitted fields on **TA** as in Fig. 2, from 85 to 100 GHz, in cases of (a) TM and (b) TE incident; the positions of anticipated Δt_as by the proposed method at varying frequencies, are also marked.

4. CONCLUSION

In this paper, we further discussed the beam transmission shift through FSS based on the method reported in [11]. The longitudinal beam shift is discussed, which is found to be with a smaller effect on the transmitted beams through FSS. We also considered another FSS structure to perform the tangential beam shift anticipation, and accurate results were obtained. That means the tangential shift anticipation method in [11] can be utilized regardless of FSS structure types.

REFERENCES

1. Foster, L. P. R. and R. J. Wylde, "The effect of quasi-optical errors on reflector antenna performance," *IEEE Trans. on Microwave Theory Technique*, Vol. 40, No. 6, 1318–1322, 1992.
2. Costes, L., C. Bushell, M. J. Buckley, and G. Mason, "Microwave humidity sounder (MHS) antenna," *Proc. SPIE*, Vol. 3870, Florence, Italy, Dec. 1999.
3. Jorgensen, R., G. Padovan, P. de Maagt, D. Lamarre, and L. Costes, "A 5-frequency milimeter wave antenna for a spaceborne limb sounding instrument," *IEEE Trans. on Antennas Propagat.*, Vol. 49, No. 5, 2001.
4. Goldsmith, P. F., *Quasioptical Systems: Gaussian Beam Quasioptical Propogation and Applications*, Wiley-IEEE Press, New York, 1998.
5. Dickie, R., R. Cahill, H. S. Gamble, V. F. Fusco, A. G. Schuchinsky, and N. Grant, "Spatial demultiplexing in the sub-millimeter wave band using multilayer free-standing frequency selective surfaces," *IEEE Trans. on Antennas Propagat.*, Vol. 5, No. 6, 1904–1911, 2005.
6. Pasian, M., M. Bozzi, and L. Perregrini, "Accurate modeling of dichroic mirrors in beam-waveguide antennas," *IEEE Trans. on Antennas Propagat.*, Vol. 61, No. 4, 1931–1938, 2013.
7. Donnan, R. S. and A. Yamsiri, "Accurate modeling of dichroic mirrors in beam-waveguide antennas," *EuCAP 2007*, Nov. 2007.
8. Prakash, V., N. T. Huang, and R. Mittra, "Accurate analysis of interaction between microwave antennas and frequency selective surface (FSS) radomes," *ICAP 2003*, Vol. 1, 401–404, 2003.
9. Jin, M., M. Bai, N. Ou, and J. Miao, "The plane-wave spectrum approach for beam transmission through planar FSS structures," *IEEE ICMMT 2012*, 2012.
10. Bai, M., M. Jin, N. Ou, and J. Miao, "On scattering from an array of absorptive material coated cones by the PWS approach," *IEEE Trans. on Antennas Propagat.*, Vol. 61, No. 6, 3216–3224, 2013.
11. Jin, M. and M. Bai, "On the transmitted beam shift through FSS structure by phase analysis," *IEEE Antenna Wireless Propagat. Lett.*, Pre-published online.
12. https://www.cst.com/Products/CSTMWS.