Development of Magneto-static Solver Module for the design of compact and light-weight Traveling Wave Tubes

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Abstract- Traveling Wave Tubes are the unique class of microwave amplifiers with broad bandwidth, which makes it preferred for space applications. The constraints for a space application are very stringent demanding compactness and less weight. Entire size of the tube is mainly decided by the size of the collector, as it is the bulkiest component in a tube. Hence, if the size of the collector is reduced then the entire tube size will reduce. Researches reveal that in order to reduce the size of the collector, application of the magnetic field is necessary. Therefore, to study the effect of magnetic field on the collector performance, a magneto-static solver module has been developed. This paper describes the development of the magneto-static solver.

1. Introduction
Traveling Wave Tubes (TWTs) are the most preferred microwave amplifiers used for space application. The reason behind this is that only TWTs are able to satisfy almost all of the space requirements. Major constraints imposed to qualify for space include high efficiency, compactness, less weight, high reliability and long life. These requirements are critical to achieve and many of these are even contradictory. Hence, achieving all, at the same time, becomes a big challenge.

A TWT consists of mainly electron gun, slow wave structure, couplers (both input and output), magnetic focusing system and collector. Overall efficiency of TWT is decided by its electronic, circuit and collector efficiency [1]. Among these efficiencies, attaining high collector efficiency is of prime importance because most of the power is wasted as heat in collector region only. High efficiency in collector is achieved by various techniques like multi-stage depression [2], modification of collector geometry [3– 6], using secondary electron suppression coatings etc [7, 8].

Further, size and weight of a TWT largely depends on the collector, as collector is comparatively larger and heavier than other components of TWT. Hence, reducing the collector dimensions will yield compactness and light weight to the tube. But, generally the overall diameter of the collector depends on the universal beam spreading nature of the beam due to space charge effect. Hence, any attempt to reduce the size of the collector can be fruitful only if magnetic field is applied on the collector region [9]. In order to study the effect of magnetic field on collector performance, a magneto-static solver module is needed. Therefore, the authors were motivated to develop the magneto-static solver module.

The objective of a magneto-static solver module is to compute the static magnetic field profile around the magnet. The magnetic field configurations generally used in any TWT, may be, free permanent magnet, solenoid or periodic permanent magnet. The magneto-static solver module in its present form has the feature to simulate any of these magnetic configurations. The theory for the
development of the magneto-static solver module is described in section 2. All simulation results
along with their corresponding validation, done in CST STUDIO SUITE [10], are included in section
3. Final concluding remarks are mentioned in section 4.

2. Theory
Determination of magnetic field components in vicinity of a magnet can be done by any of the
following methods, as mentioned in [11],

- Method based on determining the distribution of microscopic ampere’s current
- Method based on the Poisson and Laplace equations, determining the magnetic scalar
  potential
- Method based on a system of equivalent magnetic dipoles (superposition of elementary results
  obtained for elementary magnetic dipoles)

2.1 Free Permanent Magnet
Permanent magnets are basically ferromagnetic materials. Free permanent magnets can be used at the
entrance of the collector region so that the axial magnetic field produced by these magnet aid in better
collection of the electrons.

For magnetic material with straight line normal demagnetization curves, it is possible to calculate
with reasonable accuracy the flux density at a distance X from the pole surface, on the magnet’s
centerline [11].

- Rectangular magnet

Fig. 1. Geometry of free rectangular permanent magnet

\[
B_x = \frac{B_r}{\pi} \left[ \tan^{-1} \left( \frac{AB}{2X\sqrt{4X^2 + A^2 + B^2}} \right) - \tan^{-1} \left( \frac{AB}{2(L+X)\sqrt{4(L+X)^2 + A^2 + B^2}} \right) \right]
\]

- Cylindrical magnet

Fig. 2. Geometry of free cylindrical permanent magnet

\[
B_x = \frac{B_r}{2} \left[ \frac{(L+X)}{\sqrt{R^2 + (L+X)^2}} - \frac{X}{\sqrt{R^2 + X^2}} \right]
\]
2.2 Solenoid

The magnetic field around a solenoid can be derived by computing the magnetic vector potential [12]. Magnetic fields are produced by currents, which have associated directions. Hence, it is obvious that magnetic potential is a vector quantity. The magnetic vector potential is high in the vicinity of currents and tends to have the same direction as the currents which produce it.

The radial and axial magnetic flux density expressions are derived to be,

\[ B_r = \frac{B_{z0}}{2} \left[ \sum_{n=0}^{\infty} \frac{(-1)^n}{2^n n!} L^n \right] \]

\[ B_z = \frac{B_{z0}}{2} \left[ \sum_{n=0}^{\infty} \frac{(-1)^n}{2^n n!} L^n \right] \]

where \( B_{z0} \) is the magnetic flux density at the axis.

The magnetic flux density along the axis of a circular coil is found experimentally to be approximately,

\[ B_{z0} = \frac{\mu_0 a^2}{2} \frac{NI}{(a^2 + z^2)^{3/2}} \]

where, \( a \) – radius of the coil, \( N \) – number of turns and \( I \) – current flowing through the coil. The degree of approximation is fairly good, if the dimensions of the winding cross-section are small compared with coil radius.

2.3 Periodic Permanent Magnet

Periodic permanent magnet (PPM) structure is most commonly used for focusing of the electron beam in slow wave structure of a TWT. It generally consists of an assembly of ring-shaped magnet separated by soft iron pole pieces, as shown in figure 4. A practical PPM configuration used in a TWT consists of more than 25 such assemblies of ring magnet and pole piece.

The analysis of the PPM structure can be done in a simplified way by analyzing only a half-period PPM cell (next half period will only change in polarity), neglecting the end effects and taking advantage of periodicity and symmetry [13].

- Calculate total permeance of all flux paths
- Calculate the load line slope
- Determine the operating point of the magnet
- Finally, compute axial magnetic field which is given by,

\[ B_z(z, r) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4B_{z0} \sin \left( \frac{n \pi y_1}{L} \right)}{I_0 \left( \frac{2n \pi y_1}{L} \right)} \frac{I_0 (2n \pi r/L)}{\cos \left( \frac{2n \pi z}{L} \right)} \]
Fig. 4. Geometry of periodic permanent magnet

3. Validation of Results

Above mentioned theory has been implemented in MATLAB and a magneto-static solver module has been developed. The module is developed in a user friendly manner with good graphical user interfaces. The results of each of the magnetic configurations with their validations are as follows.

3.1 Free Permanent Magnet

Permanent magnets are basically ferromagnetic materials. Free permanent magnets can be used at the entrance of the collector region so that the axial magnetic field produced by these magnet aid in better collection of the electrons. For magnetic material with straight line normal demagnetization curves, it is possible to calculate with reasonable accuracy the flux density at a distance X from the pole surface, on the magnet’s centre line [11].

- Rectangular magnet

A rectangular free permanent magnet with all dimensions - length, breadth and width, taken as 1mm (similar to a unit cube) has been simulated. The remanant magnetic flux density has been set to 1T. The comparison of the magnetic field profile along axial direction, obtained from the magneto-static solver and CST STUDIO SUITE is shown below in figure 5.

![Comparison of the B field along Z direction obtained from (i) MATLAB Magneto-static solver, (ii) CST STUDIO SUITE](image)

From figure 5, it is evident that both the profiles match approximately but not accurately. The reason for this deviation is that several approximations and assumptions were taken during the analytical derivation of the expression for magnetic field. Flux linkage effects were not taken into account while the derivation of magnetic field expression but CST STUDIO SUITE considers all the flux linkages. This is the obvious reason for this deviation.

- Cylindrical magnet

Cylindrical free magnet of radius 1mm and length 1 mm has been simulated with remanant magnetic flux density, 1T. The validation of magnetic field profile along axial direction obtained from the magneto-static solver by the ones obtained by CST STUDIO SUITE, are depicted below in fig. 6.
It could be observed from the above results that both the profiles agree closely, except for quiet smoothness at the tip of magnetic field, obtained by this magneto-static solver module. Again this is due to the negligence of flux linkage effect in the analytical expression.

- Ring shaped magnet
  
  A ring-shaped free permanent magnet of outer radius 2mm and inner radius 1 mm with unit thickness has been simulated with remanant magnetic flux density of 1T. The comparison of axial magnetic field profile obtained by this magneto-static solver and by CST STUDIO SUITE is shown in figure 7, side by side, and could be observed to have very good agreement between them, thus validating the magneto-static solver module for free permanent magnets.

3.2 Solenoid

Solenoid of diameter 30mm, length 15mm and 100 turns has been simulated with remanant magnetic flux density of 1T. The 2D results for the B field obtained from the magneto-static solver and CST STUDIO SUITE are displayed below in figure 8.

The figure 8 depicts the 2D patterns of the radial magnetic field. From the above comparisons, it is evident that magnetic field patterns agree though having slight deviations. The deviations are due to the fact that, in the field expression of Br and Bz, only finite number of terms (in particular only four terms) are taken into account. Accurate field patterns could be obtained only if an infinite series is taken into account. But, in the implementation of the magneto-static solver, it was assumed that later terms will be of very small value to affect the accuracy and hence was avoided, which led to the deviation in the magnetic field patterns.

3.3 Periodic Permanent Magnet

A periodic permanent magnet configuration has been simulated whose dimensions and demagnetization properties have been taken from [13]. The axial magnetic field profile has been obtained by the magneto-static solver as shown in figure 9. This agrees very closely with the published result [10], which is also shown for comparison below.
Fig. 8. Comparison of the 2D results of radial B field obtained from (i) MATLAB Magneto-static solver, (ii) CST STUDIO SUITE;

Fig. 9. Comparison of the B field along axis (i) MATLAB Magneto-static (ii) Published work

4. Conclusions
The development of the magneto-static solver has been elaborated for various magnetic configurations. From the results obtained, it can be concluded that magneto-static solver has very good agreement with CST PARTICLE STUDIO and thereby validating it.

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