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Magnetic Circuit for a Sheet Electron Beam Ka-band Microfabricated Traveling Wave Tube

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Abstract—A magnetic circuit for a sheet beam Ka-band microfabricated traveling wave tube (TWT) is presented in this paper. The magnetic circuit is designed to provide a uniform solenoidal magnetic field to keep the sheet beam focused. The design of the magnetic circuit has been optimized using the CST EM STUDIO. Neodymium Magnets and Consumet® Electronic Iron have been selected as the materials of magnets and pole pieces in this design, respectively. Simulation results are presented in the form of 3-d vector magnetic field plots. The results show that the magnetic circuit can produce a uniform magnetic field of 0.21 T over a distance of 40 mm. To assemble the magnetic circuit, an aluminum fixture is designed and fabricated to hold the magnets and pole pieces together. Measured results show an excellent match with the simulation results.

Keywords—Neodymium; permanent magnet; uniform; magnetic field

I. INTRODUCTION

Millimeter wave frequencies have very important applications in modern society. In particular, the Ka-band (26.5–40 GHz) is very useful in communications satellites and high-resolution, close-range targeting radars aboard military airplanes.

Due to more reliable performance at high power levels, higher efficiency, and lower cost and weight per watt, vacuum electron devices (VEDs) are widely used as microwave and millimeter wave oscillators and amplifiers. A traveling-wave tube (TWT) is a specialized VED that is used to amplify radio frequency (RF) signals from GHz to THz range. Among the different types of VEDs, TWTs are noteworthy due to their large bandwidth and linearity. Communications satellites, airborne radar systems and UAVs commonly use TWTs.

Schematic of a common type of TWT is shown in Fig. 1. An electron beam is one of the most important parts in TWTs. The electron beam is produced and accelerated by an electron gun, and in this process, the electron beam acquires power from a high voltage DC power supply. The electron beam enters and drifts in the center of a slow wave structure (SWS) which guides an electromagnetic wave. Once the velocities of the electron beam and electromagnetic wave satisfy the synchronous condition, the beam wave interaction occurs. In a TWT, the velocity of the electron beam is slightly higher than the phase velocity of the electromagnetic wave. As a result, the electron beam transfers DC energy to the electromagnetic

Fig. 1 Schematic view of a helix traveling wave tube (Thales Electron Devices GmbH).

Fig. 2 Perspective view of the microfabricated traveling wave tube using PH-SEC SWS.

wave. The efficiency of this beam wave interaction depends on the shape and current density of the electron beam directly.

Because of the space charge force among the adjacent electrons in an electron beam, an electron beam tends to diverge as it is transmitted through the SWS. So an external force is necessary to maintain the electron beam shape in TWTs. Numerous electrostatic focusing techniques have been examined since microwave tubes have been in existence. With the exception of very few cases where the tube is designed to accommodate a beam following the universal beam-spread curve, in which case no focusing is required, only magnetic focusing is used at the present time [1]. In TWTs, the focusing forces are provided by a magnetic field aligned with the axis of the electron beam. The magnetic field is generated using permanent magnets.

Sheet electron beams are advantageous for millimeter-wave and higher frequency vacuum electron devices. Sheet beams

Fig. 3 Magnetic circuit to provide uniform solenoidal focusing magnetic field.

TABLE I.
DIMENSIONS OF THE MAGNETIC CIRCUIT

Symbol	Value (mm)	Symbol	Value (mm)
lp_1	124	dm_1	17
lp_2	32	dm_2	50
hp_1	10	dp	60
hp_2	20	hm_1	9
w	25	hm_2	9
lm_1	37	w_2	8
lm_2	53.5	h_2	8

offer higher beam current capacity, decreased beam voltage, lower magnetic field requirement and increased bandwidth. On the other hand, focusing of sheet beams is more challenging than that for beams of circular cross-section. There are several types of magnetic fields which can be used to focus a sheet electron beam. These types include periodic permanent magnet (PPM) and periodic cusped magnet (PCM) [2]. But by a proper design, a uniform solenoidal magnetic field can also guarantee good beam transmission [3].

Recently, a sheet electron beam Ka-band microfabricated TWT has been proposed by our group [4], of which the perspective view is shown in Fig. 2. This TWT is based on a planar helix SWS with straight-edge connections (PH-SEC). The PH-SEC has wideband properties similar to a circular helix and is compatible with microfabrication. The view in Fig. 2 includes the cathode, beam-forming electrode, anode, and the PH-SEC SWS. The proposed TWT uses an e-beam with beam voltage of 3.72 kV and current of 10 mA which is applied centrally in the electron-beam tunnel. The elliptical cross section of the e-beam has a major axis of 350 μm and a minor axis of 150 μm .

A uniform solenoidal magnetic field is selected as the focusing field here because of relatively simple design of the magnetic circuit and ease of implementation. To focus the electron beam in the design presented in [4], a magnetic field of 0.21 T that is uniform over a distance of 40 mm is needed. In this paper, design, fabrication and test of such a magnetic circuit are presented for the first time.

Fig. 4 Magnetic field produced by the magnetic circuit. (a) Vector magnetic field in the yz plane, (b) vector magnetic field in the xz plane, (c) z-component of the magnetic field.

Section II describes the design of the magnetic circuit and the simulation results for the magnetic field. Section III describes the design and fabrication of a fixture to hold the magnetic circuit. The assembly and the test results of the magnetic circuit are described in Section IV.

II. DESIGN OF THE MAGNETIC CIRCUIT

The magnetic circuit should produce a uniform magnetic field along the axis of the SWS. The design of the magnetic circuit [5] is optimized by using the CST EM STUDIO [6] and the final design is shown in Fig. 3. As can be seen, it consists of 8 magnets (blue and grey) and 6 pole pieces (red and yellow ones). The main dimensional parameters are also labeled in the figure.

The magnets are Neodymium Magnets, the residual flux density and maximum energy product of which can be as high as 1.4 T and 52 MGOe. The pole pieces are made of high permeability Consumet® Electronic Iron. The whole gun, SWS, and collector fit between the yellow pole pieces marked '2' in Fig. 3. The length of the magnetic circuit is designed accordingly. Since these items have a small cross-section, the pole pieces marked '2' can accommodate these.

Fig. 5 Front view of the fixture designed for the magnetic circuit.

Fig. 6 Photograph of the fabricated aluminum fixture.

The direction of magnetization of the magnets is along the y-direction. In the simulations, the magnetization type is selected as Constant and the y-component of the Remanent magnetization is set to 1.25 T. With this setting, a single magnet is simulated first, yielding a surface magnetic field of 0.2794 T. In comparison, the surface magnetic field obtained in measurements is 0.2790 T.

Fig.4 (a) and (b) show the vector magnetic field produced by the magnetic circuit using the dimensions listed in TABLE I. Fig.4 (a) shows the vector magnetic field in the $x = 0$ plane and Fig. 4 (b) shows the field in the $y = 0$ plane. It is assumed that the origin is located at the centre of the circuit. Fig. 4 (c) shows the variation of the z-directed magnetic field along the z-axis. These figures show that the axial magnetic field is quite uniform at the location of the beam tunnel and has a value of about 0.21 T in the range $-20 \text{ mm} < z < 20 \text{ mm}$.

III. DESIGN OF THE FIXTURE TO HOLD THE MAGNETIC CIRCUIT

We can see from Fig. 4 (a) that the upper and lower magnets will repel from each other. Therefore the entire magnetic circuit cannot be held together without external force. Considering the strong magnetization of the magnets, a metal fixture is a better option than bonding the pieces together with glue. Moreover, a fixture allows assembly and dis-assembly of the magnetic circuit much more easily.

Fig. 7 Assembled magnetic circuit and fixture (inside a polythene wrapper).

Fig. 8 Test set-up for the magnetic circuit.

The simulation results show that the magnetic field produced by the magnetic circuit placed inside a non-magnetic fixture is the same as that shown in Fig. 4. We should note that magnets 1 and magnets 2 are chosen to have identical dimensions in order to reduce the fabrication cost, although if one uses different heights of these magnets, one can achieve a flatter magnetic field curve, i.e., a more uniform magnetic field.

Fig. 9 Comparison between the simulation and measured results of the z-component of the magnetic field for the magnetic circuit.

Fig. 5 shows the front view of the fixture designed for the magnetic circuit and Fig. 6 shows the photograph of the fabricated fixture. As can be seen, the fixture is fabricated by milling a trench in an aluminum block. The outline of the trench matches that of the magnetic circuit. In the center of the magnetic circuit, where the Ka-band microfabrication TWT will be placed, a long horizontal slot is milled out. This slot has the same width and height as the rectangular hole in the pole pieces 2 shown in Fig. 3.

As shown in Fig. 6, the corners in the trench have to be rounded and enlarged while the other dimensions closely match that of the magnetic circuit. The outer walls of the trench are slightly higher than the central walls to provide a stronger constraining force for the magnetic circuit. Vertical walls of the trench are also given a gentle slope to make the assembly and dis-assembly of the magnetic circuit much easier.

IV. ASSEMBLY AND TEST

The magnetic circuit assembled in the fixture and wrapped in polythene is shown in Fig. 7. The wrap is to protect the magnets from air and water, as the iron is easily oxidized in wet air. The magnets and pole pieces are fitted into the fixture according to the arrangement shown in Fig. 3.

Fig. 8 shows the test set up for the magnetic circuit. A gaussmeter (model No. G91 by Coliy Tech) with a transverse probe (model no. T08P150G91) is used to measure the magnetic field strength. The probe of the gaussmeter is attached firmly to a three dimensional movement platform made of a nonmagnetic material. The platform enables one to move the probe in the x, y, and z directions manually with a positioning accuracy of 0.1 mm.

The magnetic circuit is tested in the range $0 \text{ mm} \leq |z| \leq 29 \text{ mm}$ and $57 \text{ mm} \leq |z| \leq 65 \text{ mm}$. In the range $29 \text{ mm} \leq |z| \leq 57 \text{ mm}$ are the pole pieces 2, where our probe cannot enter. The axial magnetic field at the center of the magnetic circuit is measured to be 2029 Gauss. A comparison between the simulation and measurement results is shown in Fig. 9. As can be seen, the measured results match the simulation results very well in the entire range. Thus the magnetic circuit can produce the required uniform magnetic field of $\sim 0.21 \text{ T}$ over a distance of 40 mm.

V. CONCLUSION

A magnetic circuit for a sheet beam Ka-band microfabricated traveling wave tube (TWT) has been described. The sheet beam has a beam voltage of 3.72 kV and current of 10 mA. The elliptical cross section of the e-beam has a major axis of $350 \text{ }\mu\text{m}$ and a minor axis of $150 \text{ }\mu\text{m}$. The magnetic circuit has been designed to provide a uniform solenoidal magnetic field of 0.21 T to focus the sheet beam. Neodymium Magnets, and Consumet® Electronic Iron have been selected as the materials of magnets and pole pieces, respectively. Simulation results for the vector magnetic field are presented. An aluminum fixture has been designed and fabricated to hold the magnets and pole pieces of the magnetic circuit together. The magnetic circuit assembled in the fixture is tested with the help of a gaussmeter, a probe, and a 3-d movement platform. The test results match very well the simulation results and confirm that the magnetic circuit can produce a uniform magnetic field of 0.21 T over a distance of 40 mm.

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