APPLICATION NOTE 12

HOW A HELIX BACKWARD-WAVE TUBE WORKS

The backward-wave oscillator provides a flexible source of microwave energy that can be voltage tuned over bandwidths from 1.5:1 to as high as 5:1. The output frequency of the backward-wave oscillator is determined by a frequency-selective feedback and amplification process rather than by resonant circuits as used in conventional microwave oscillators.

The backward-wave oscillator tube consists of: an electron gun, a helix structure and a collector at the far end of the helix (see Figure 1). Physically, the backward-wave oscillator resembles the traveling-wave amplifier tube; although, for comparable frequencies it is larger in diameter and somewhat shorter in length. Another difference, not apparent from a visual inspection of the tube, is that the helical backward-wave oscillator uses a hollow electron beam with a strong concentration of the electrons near the helix. This hollow electron beam is focused along the length of the helix by a strong magnetic field supplied by an axial solenoid surrounding the tube.

The rf output of the backward-wave oscillator is a result of the interaction between the electron beam and the electric fields accompanying a microwave signal present on the helix. The term "backward-wave oscillator" is quite appropriate for this tube since the rf energy moves and builds up in a direction opposite to that of the electron beam and is coupled out at the gun end of the tube via the helix terminal.

The operation of the backward-wave oscillator tube may be explained in terms of a series of feedback loops similar to those common to low frequency electronic circuits. Each of these regenerative loops can function as an amplifier or an oscillator and is designed so that the phase shift around the loop is one cycle. One of these feedback loops is shown in Figure 2 where, using conventional terminology, the forward or μ circuit consists of a section

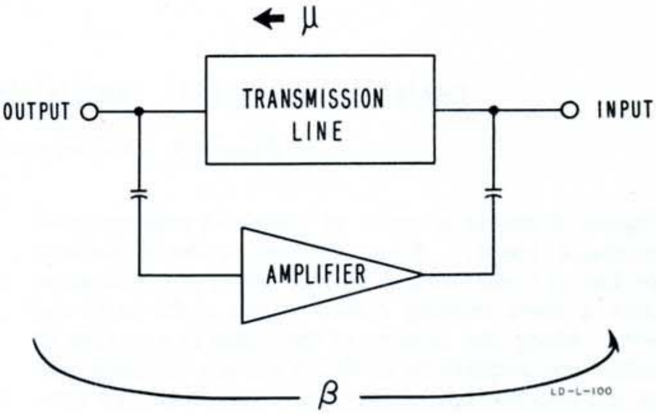

Figure 2. A Single Regenerative Loop

of transmission line and the backward or β circuit is a unilateral amplifier connecting the output of the transmission line to the input. In this circuit positive feedback will occur when the amplifier gain becomes sufficiently high to overcome the loss in the transmission line and the $\mu\beta$ loop will oscillate at a frequency for which the total phase delay is one or more cycles. If the amplifier is designed for limited high frequency response, oscillations will occur only when the phase delay is one cycle and the frequency of oscillation can be shifted by changing the phase delay in the amplifier. The essential feature of the voltage-tuned backward-wave tube oscillator is that the frequency of oscillation can be changed electrically by changing the phase delay in the amplifier.

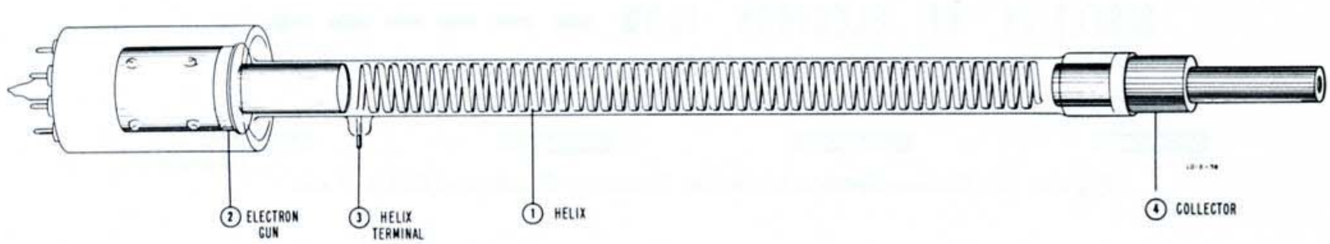

Figure 1. Backward Wave Oscillator Tube

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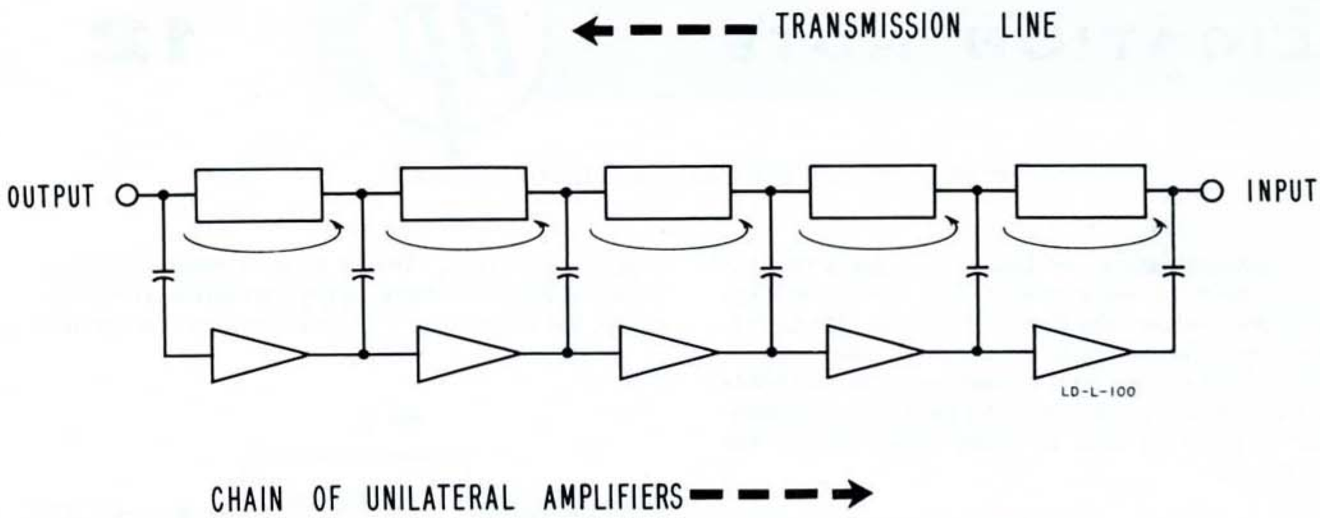

Figure 3. A Chain of Regenerative Loops

Figure 3 shows a chain of identical regenerative feedback loops. Along the top of the chain is a series of transmission line sections that will support a wave moving either to the right or to the left. Along the bottom of the chain is a series of unilateral amplifiers in which signals can pass only in the left-to-right direction. Each loop then consists of a transmission line, two coupling capacitors and an amplifier transmitting from left to right. In operation, positive feedback, which leads to regenerative amplification or oscillation, occurs utilizing a wave going from right to left on the transmission line when the phase delay in a single loop is just one cycle. The total phase delay around a group of n loops will then be n cycles.

For low values of amplification, the chain of loops will act as a regenerative amplifier operating at the frequency which provides positive feedback. However, if the transmission line is terminated in its characteristic impedance at the input and the amount of amplification is increased, oscillations will start. The frequency of oscillation will be controlled by the phase delay in the amplifier chain.

With this background we can now examine the actual functioning of the backward-wave oscillator tube. Figure 4 shows a cross section of the helix and a

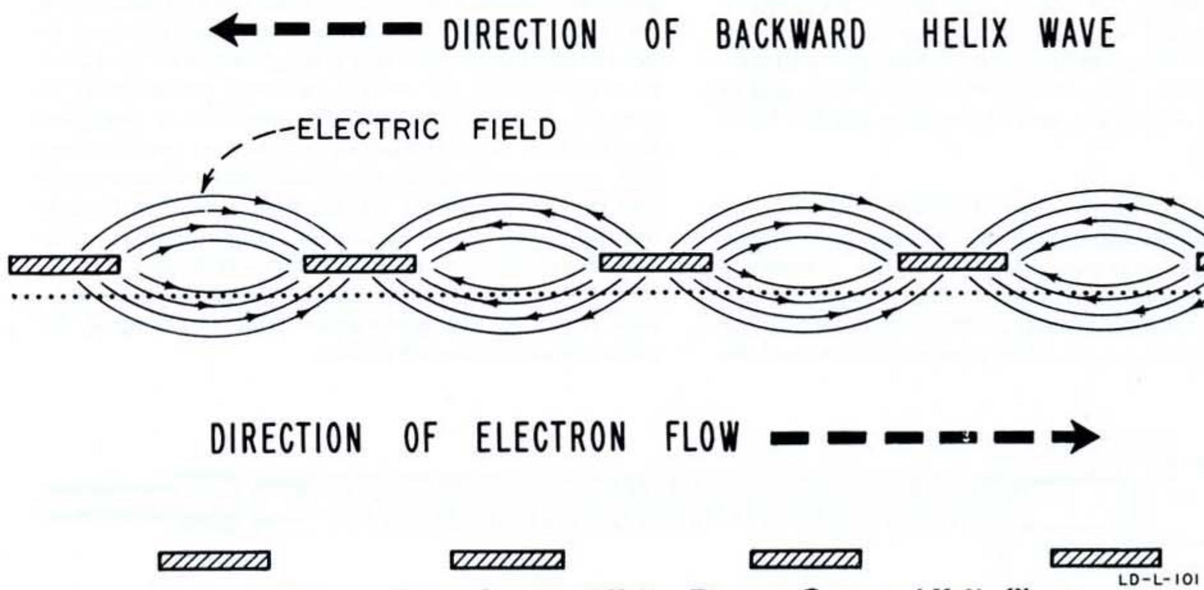

Figure 4. Cross-Section of Helix, Electron Beam and Helix Wave

portion of the electron beam. The helix structure consists of a cylindrically-wound flat-wire tape; the electron beam is hollow and passes very close to the helix turns. The strong axial magnetic field focuses the electrons in the beam and allows movement only in the direction of the axis of the tube. The lines of force of the electric fields associated with an rf wave traveling along the helix are also shown in Figure 4. Although these fields rotate around the helix at the velocity of light equal to the ratio of the turn-to-turn spacing of helix divided by its circumference. The axial electric fields will be strong between helix turns and very weak under the turns since electric fields cannot exist parallel to a conductor. The strong effect of these fields between helix turns on the velocity of the electrons in the beam produces an interaction process which is represented by the capacitive coupling between the transmission line and the amplifier chain shown in Figure 3. In this way, feedback loops are formed between the mid-points of adjacent helix gaps.

Although the concept of discrete feedback loops is a useful device for explanation, the backward wave interaction is actually a continuous process. The maximum coupling between the helix wave and the beam will occur mid-way between gaps and gradually taper off to a minimum directly under the helix turns. One of these regenerative loop chains exists at each angular position around the helix. Each of these regenerative loop chains is independently coupled to the helix transmission line, so the net effect is a continuous amplification and feedback process occurring down the entire length of the tube.

The basic mechanism of amplification is a velocity modulation process which causes the electrons to bunch in the beam. Figure 5 shows the sinusoidal variations in amplitude of the electric field at the mid-point between helix turns. The phase relationship between the backward wave on the helix and

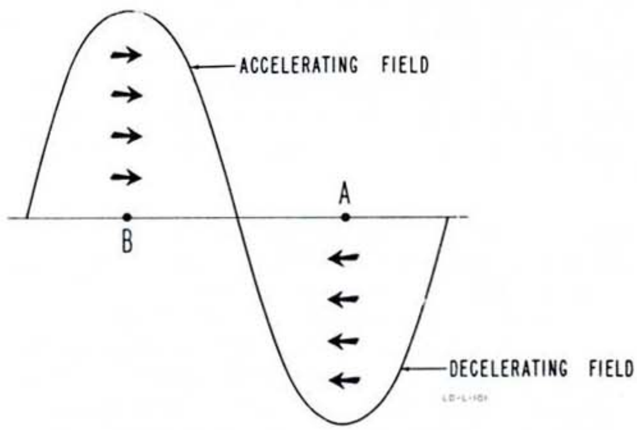

Figure 5. Axial Electric Field of Helix Wave which provides Velocity Modulation and Bunching of Electron Beam

the velocity of the electron beam is such that each specific portion of the electron beam will be affected by an electric field of the same phase as it passes successive gaps down the helix. Referring to Figure 5, an electron at Point A experiencing the decelerating effect of the field at the first gap in the helix will experience a continuous decelerating effect caused by fields of the same phase and direction of force as it proceeds down the tube. In a like manner, an electron at Point B will be continuously accelerated in its journey down the tube. In this way, some parts of the electron beam are slowed down while others are advanced and the net effect is a bunch formed at the mid-point of Figure 5 between the accelerating and decelerating fields. This situation is shown in Figure 6. The spiral form of the bunched electron beam is due to velocity modulation which occurs at different rf phases at various angular positions around the spirally wound helix.

At this point it should be mentioned that the average electron velocity of the beam is slightly faster than

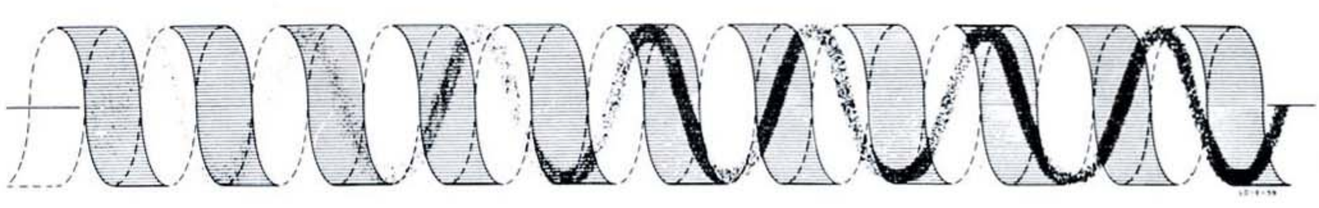

Figure 6. Helix Showing Bunching of Electron Beam

the effective phase velocity of the amplifier chain. This means that the electron bunches will advance a quarter of a cycle as they approach the collector end of the tube, and thus encounter the full decelerating effects of the electric field and give up a maximum amount of kinetic energy to the wave on the helix.

Figure 7 shows that the density of the electron bunches increases according to a sine-wave relationship; Figure 7 shows the envelope of the bunching rather than instantaneous amplitudes since many rf cycles cxist along the length of the backward-wave oscillator tube. The wave on the helix moves from right to left towards the gun end of the tube and gains amplitude between each turn according to the degree of electron bunching in the beam. In this way, the envelope of the wave on the helix shown in Figure 7 is the integral of the bunching envelope so the maximum energy transfer from the beam to the wave on the helix occurs at the collector end of the tube.

Now that a correspondence between the chain of lumped regenerative loops and the helix backward wave oscillator tube has been established, it can be seen that if the velocity of the electron beam is varied, the phase delay around each of the regenerative loops will be changed and, if the electron beam current is high enough, the chain of regenerative loops will oscillate at a frequency where the phase delay of each loop is equal to one cycle.

Oscillations begin in the backward-wave oscillator in much the same manner as they begin in other oscillators. Noise waves are established on the helix from the shot noise coupled from the electron beam and from thermal energy developed in the termination at the input end of the tube. The waves traveling backward on the tube (to the left) velocity modulate the beam. Velocity modulation causes the electrons to bunch and in turn reinforce the wave that exists on the helix at the frequency where the single loop delay is equal to one cycle. In this way, oscillations are built up at a single frequency determined solely by the electron beam velocity which is a function of the cathode to helix voltage of the tube.

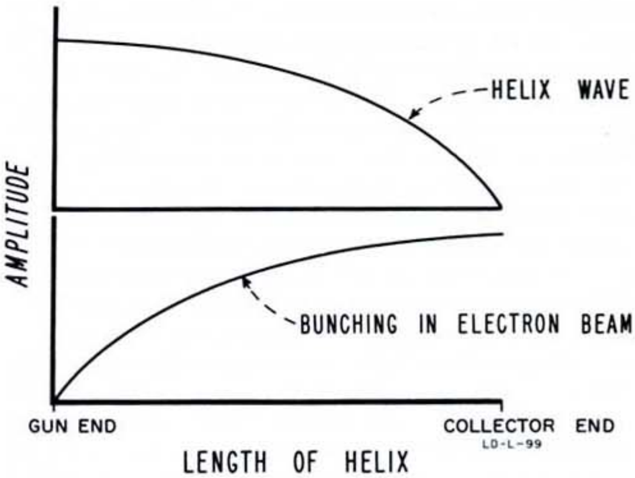

Figure 7. Relative Amplitude of the Envelope of the Helix Wave and the Degree of Electron Bunching along Helix.