Superconducting soliton device.

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RAJEVKUMAR: "A Soliton Device", pages 591-594

Proprietor: International Business Machines Corporation
Old Orchard Road
Armonk, N.Y. 10504 (US)

Inventor: Rajeevakumar, Thekkemadathil V.
4 Dova Court, N.
Croton-on-Hudson New York 10520 (US)

Representative: Schröder, Otto, Dr. Ing.
Säumerstrasse 4
CH-8803 Rüschlikon (CH)

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The invention relates to a superconducting soliton device for guiding Josephson solitons into selected transmission lines. The device comprises an input transmission line and at least two output Josephson transmission lines intersecting the input line at a common intersection, these input and output lines being capable of supporting Josephson solitons therein. Furthermore provided are control means for steering solitons arriving at the intersection into a selected one of the output lines.

Josephson devices are known in the art and have primary advantages in that they display low power dissipation (about 1 microwatt) and fast switching (approx. 100 pico-seconds). These are attributes for use as elements in super fast computers and they have been suggested for this application. The progress in the superconductive technology, and in particular the development of Josephson devices for memory and logic, has been quite substantial in the past decade.

Even prior to the discovery of the Josephson effect, it was pointed out that certain basic problems in larger scale integration and in extreme miniaturization of electronic circuits may require new types of device structures. For example, although device dimensions decrease with decreasing line width, the number of connections per device remain more or less the same. Distributed device structures that avoid attenuation and dispersion of signals, and novel system concepts have been suggested in the art as alternatives. Further, the concept of distributed devices can easily be extended to the Josephson technology; however, only limited progress has been made so far as is apparent from K. Nakajima et al, J. Appl. Phys., 47, 1620 (1976); T. A. Fulton et al, Appl. Phys. Lett., 22, 232 (1973); and T. A. Fulton et al, Proc. IEEE 61, 28 (1973).

The present invention describes a distributed Josephson logical device based on the principle of selective control of the movement of Josephson solitons. These are isolated fluxoid, of a type known in the art and described more completely in J. Rubenstein, J. of Math. Phys. 11, 288 (1970); A. C. Scott, Nuovo Cimento B69, 241 (1970); and T. A. Fulton et al, Solid State Comm. 15, 57 (1973); and T. V. Rajeev, Kumar et al, Phys. Rev. B27, 5432 (1980). It is known in the art that a Josephson transmission line (i.e., a long one dimensional Josephson junction) can support the propagation of Josephson solitons as reported by the aforementioned T. V. Rajeev, Kumar reference. The solitons can be generated in the Josephson transmission line by known techniques and can be made to propagate and accelerate through the Josephson transmission line under the influence of the Lorentz force due to a bias current in the Josephson line.

The concept of using a soliton, or fluxoid, to carry information is known in the art, as is the concept of moving these information-representing solitons along the Josephson transmission line. Further, it is known that a soliton brought to the intersection of Josephson transmission lines can be made to follow one or another path away from the intersection. This is described in the Nakajima reference described previously, where that concept is used for the design of logic networks. In that paper, the authors describe "turning points" of two types: in one type a single flux quantum propagating to the trigger turning point (TTP) on any one line will initiate a single flux quantum on all connected lines, and in the other type, a second turning point named the selective turning point (STP), a single flux quantum propagating toward the point on any one line will initiate a soliton only on one connected line. The determination of which line a single flux quantum propagates in depends upon the bias current of each line, the local applied magnetic field, and the junction geometry. Basic logic circuits using these turning points are described in this reference.

The structure of Nakajima et al has many disadvantages and is not a practical circuit. For example, the mechanism for selection of the path to be followed by the single flux quantum depends upon a delicate balance in the competition between the device internal damping (Γ), which in turn is high dependent upon the choice of device materials, the bias levels (V) of the control signals, and the choice of boundary conditions at the intersections of the turning points. Because there is these competing forces, selection of a desired path for propagation of the soliton depends on factors other than just the presence or absence of the control signal. This means that the margins for path selection are very limited. Furthermore, any variations in device design across the chip or in the geometry of the various devices will lead to problems. Still further, the two types of turning points require different structure, and for this reason the logic chip will have to be fabricated from devices having different designs. This puts an additional constraint on the fabrication and on the number of masking steps which are required.

In the Nakajima et al circuits, undesired solitons will be generated at the turning points and these will not be easily removed. Also, effective isolation between the output of the device and the input is not achieved when the control signals are directly coupled to the Josephson transmission lines. Additionally, in LSI circuits it is desirable to use the same control signal amplitudes throughout in order to improve circuit reliability and margins. However, in Nakajima et al, the device internal damping will vary throughout the chip and it will be virtually impossible to provide LSI circuits using that approach. Further, the need for a multitude of bias levels for control is very impractical when
large scale integrated circuits are to be provided. Still further, the multilevel junctions
required when fabricating the STP turning point leads to very difficult fabrication steps and pro-
cessing yields will be low.
Another soliton device is known from US-A-3 398 877 describing a switch in
which the transmission line supporting solitons is bifurcated. At the intersection, an arriving
soliton is split into two solitons, one each proceeding in both output transmission lines.
Control means are located in each path to selectively block or transmit the solitons. Separate
c Control circuits involving non-superconducting metal segments that interrupt the super-
conducting lines are required for each output line for selectively enhancing or impeding the
propagation of the solitons. Crosstalk between control lines, lack of electrical isolation between
the transmission lines and reflections at the intersection of these lines may cause problems
in operating the described device.
The invention as claimed is intended to remedy these drawbacks. It uses a different
mechanism for soliton path selection. Rather than having path selection depend upon a
delicate balance of competing forces, path selection in the present invention is controlled
solely by a single bias level. That is, the direction taken by the soliton at an intersection of trans-
mition lines depends only upon the presence or absence of a control signal of appropriate
polarity. Additionally, reflections of the soliton at the intersection of the transmission lines are
eliminated and unwanted solitons are destroyed at the intersection. Still further, the solution of
the present invention provides isolation between input and output circuits and is there-
fore useful in the design of logic circuits.
Several ways of carrying out the invention are described in detail below with reference to
drawings which illustrate only specific embodiments, in which
FIGs. 1.1, 1.2, and 1.3 illustrate the nature of a soliton wave (FIG. 1.1), the circulating current
\( i(x) \) in the soliton (FIG. 1.2), and the physical representation of a soliton in a long Josephson
transmission line (FIG. 1.3).
FIG. 2 is a schematic representation of an intersection of an input Josephson trans-
mision line with two output transmission lines, while FIGs. 3.1 and 3.2 are end views of the
structure of FIG. 2 taken along line 3—3, which are used to illustrate the direction of movement
of a soliton and an anti-soliton at the inter-
section.
FIG. 4 is another diagram of an end view of the structure of FIG. 2, taken along the line
3—3, wherein the bias currents in the two
output transmission lines are opposite in polarity. Thus, FIG. 4 illustrates how the soliton is
propagated in one direction by the bias control current while the anti-soliton is trapped at the
intersection.
FIGs. 5.1 and 5.2 illustrate how a resistor
located at the intersection of the input trans-
mision line and the output transmission lines can be used to dissipate the soliton or anti-
soliton trapped at the intersection when the bias currents in the two output transmission lines
have opposite polarity. In FIG. 5.1, a soliton is moved to the right, while in FIG. 5.2, an anti-
soliton is moved to the left.
FIG. 6 shows the basic soliton device of the
present invention, which can be used for unam-
biguous path selection in response to the
presence or absence of a control signal.
FIG. 7 is an electrical equivalent circuit of the
device of Figure 6, using point junctions to illus-
trate current paths in the device, while FIG. 8 is
an electrical equivalent circuit of a point junc-
tion.
FIG. 9 is a plot of a simulated voltage wave-
form at the selected output (solid line) of the
device of FIG. 6, as compared with that at the
unselected output path (dashed line).
FIG. 10 is the basic soliton steering device of
FIG. 6, except that the control currents \( I_c \)
are magnetically coupled to the device, rather than being directly injected into the device.
FIG. 11 is a schematic diagram of a two-bit
decoder using the principles of this invention
and the device of FIG. 6.
FIG. 12 is a schematic diagram of a ten-stage
chain of soliton devices which can be used to
form a decoder circuit.
In the Josephson soliton device of the
present invention there is an input transmission
line along which a Josephson soliton travels to
that intersection to dissipate the energy of a
Josephson transmission lines, means located at
the intersection to dissipate the energy of a
soliton trapped thereat, and a control means
providing a common control signal coupled
directly or inductively to both of the output
transmission lines. The path selection process is
one in which there are no competing forces and
path selection is controlled solely by the control
signal. Further, only a single bias level is
required for the control signal.
In one embodiment, the input transmission
line and the plurality of output transmission
lines have a common first electrode in the sense
that different portions of the same super-
conductor comprise one electrode of each of the
transmission lines. A tunnel barrier is provided
over this common electrode, and a second
electrode is formed over the tunnel barrier. The
second electrodes are interconnected via a
discrete resistor (such as a normal metal). A
common bias current can be injected either
directly or coupled inductively to the device via
one or more control lines overlying the output
transmission paths. The discrete resistor at the
intersection of the output transmission lines and
the input transmission line eliminates reflec-
tions of the soliton from the intersection and
destroys unwanted solitons. Additionally, it
prevents a directly injected control signal from
leaking back into the input transmission line.
Once this principle of control selection is appreciated, the design of circuits having many different functions can be achieved. A representative example is a decoder, which is described in detail.

Isolated vortices can be created and moved in long Josephson transmission lines. There are the well known Josephson solitons which are phase waves of the type shown in FIG. 1.1. In this FIG., the phase wave 10 is propagating in the +x direction with a velocity v. A circulating current is associated with the soliton and the plot of this current $I_s(x)$ as a function of the distance x is shown in FIG. 1.2. FIG. 1.3 shows the soliton represented as a circulating current loop 12 where the direction of current in the loop is represented by the arrows, and is oppositely directed on opposite sides of the loop. Soliton 12 bridges the electrodes 14 and 16 of a Josephson device, having a tunnel barrier 18 located between the superconducting electrodes 14 and 16. As will be more apparent, the phase wave comprising soliton 12 can be moved along the transmission line comprising the elongated Josephson junction of FIG. 1.3. When this occurs, a voltage pulse proportional $\frac{d\Phi}{dt}$ will be produced.

A rectangular Josephson junction whose dimensions are long and narrow compared to the Josephson penetration depth $\lambda_J$ (which are sometimes called one-dimensional junctions) can support Josephson solitons, the solitons being capable of being propagated along the rectangular Josephson junction.

In FIG. 1.3, the direction of the localized Josephson super current in the soliton is clockwise; however, it is possible to have a counterclockwise current. Depending upon the convention chosen, the isolated fluxoid 12 will be termed a soliton, or an antisoliton.

A soliton can be generated in the Josephson transmission line comprising the elongated junction shown in FIG. 1.3 by either of two known techniques. One technique is to inductively coupled magnetic flux into the Josephson transmission line, as for example by passing a current through a control line overlying (but insulated from) the transmission line. The current I in the control lines must satisfy the condition

$$\frac{1}{2} \Phi_0 \leq I \leq \Phi_0$$

where I is the mutual inductance coupled to the control line and $\Phi_0$ is the magnetic flux quantum (2.07 x 10^{-15} Wb). The second technique for generating solitons in the Josephson transmission line is to directly inject a current pulse of amplitude $I_p$ at one end, such that

$$I_p \geq 2.1 \lambda_J j_W.$$

In this expression, $\lambda_J$ is the Josephson penetration depth, $j_W$ is the Josephson current density, and W is the width of the Josephson transmission line.

The number of solitons generated by direct injection, as well as their kinetic energy, depends on the impedance of the quasi-particle tunneling inductance of the transmission line, as well as the magnitude, width, and rise and fall times of the injected pulse.

Once a soliton has been generated in a transmission line, it can be made to propagate and accelerate through the transmission line under the influence of the Lorentz force due to a bias current which tunnels from one electrode of the line to the other. In a dissipationless line, the soliton can propagate with any speed $v < c$ where $c$ is the speed of electromagnetic waves in the junction comprising the line. In a dissipative line, this could also be achieved if the bias current is sufficiently large to compensate for the dissipation.

A moving soliton or anti-soliton creates a voltage pulse V related to $\frac{d\Phi(x,t)}{dt}$, where $\Phi(x,t)$ is the position and time dependent phase difference across the two electrodes of the transmission line. When a soliton is accelerated through a biased line, the height of the associated voltage pulse increases with increasing phase velocity v and the pulse width of the voltage decreases relativistically.

In a real transmission line junction, the maximum speed of the soliton is determined by the loss and bias of the line. The bias current exerts a Lorentz force on the soliton (anti-soliton). In the steady state, the Lorentz force on the soliton due to the bias current is balanced by the drag due to quasi-particle tunneling and surface inhomogeneities. The direction of flow of the bias current, together with the polarity of the soliton, uniquely determines the direction of motion of the soliton in the transmission line.

FIG. 2 shows an input Josephson transmission line 20 which intersects with two output Josephson transmission lines 22 and 24. These transmission lines 20, 22, 24 have a common base electrode 26 and a common counter electrode 28. Although electrodes 26 and 28 are given the designation of base electrode and counter electrode, respectively, it should be understood that this is only for purposes of description. Generally, the electrode layer which is fabricated first is termed the “base” electrode, while the electrode which is formed over the tunnel barrier 30 is termed the “counter” electrode.

The presence of a bias current $I_b$ in propagating conductors 32 is used to move a soliton of appropriate polarity to the right to the intersection of output transmission lines 22 and 24. Control conductors 34 supply bias current $I_{in}$ in transmission line 22, while the conductors 36 supply bias current $I_{in}$ in transmission line 24.

FIGS. 3.1 and 3.2 are end views of the structure of FIG. 2, taken along the line 3-3. The arrows 38 across the single transmission line comprising output transmission lines 22 and 24 represent the direction of bias current $I_{in}$. Thus, there is a uniform bias across the entire line.
shown in FIG. 3.1.

If a soliton S is produced at the center of the transmission line shown in FIG. 3.1, as by propagating it to the location along input transmission line 20, or by creating a phase change of $2\pi$ at the center of the line, an anti-soliton AS is also created due to the continuity of the phase. Under the influence of the Lorentz force due to the bias current $I_b$, the soliton will drift toward one end while the anti-soliton will drift to the other end, as shown in FIG. 3.2.

In FIG. 4, a situation is shown in which each half of the transmission line is biased with a current of opposite polarity. For example, this situation would be realized in the structure of FIG. 2 if the bias current $I_b$ in transmission line 24 were oppositely directed to the bias current $I_b$ in transmission line 22. Thus, in FIG. 4 the arrows 40 are directed upward while the arrows 42 are directed downward.

The bias arrangement of FIG. 4 creates a magnetic field potential well at the center of the transmission line for the anti-soliton. When a soliton and an anti-soliton are triggered at the center of the transmission line comprising portions 22 and 24, the soliton S is steered to the right and the anti-soliton is trapped in the potential well in the center of the transmission line.

FIGs. 5.1 and 5.2 depict a situation in which a resistor R is located at the center of the transmission line and is connected between the two portions of the electrode 28. In FIG. 5.1, the bias current $I_b$ on the left hand end of the transmission line is oppositely directed from that on the right hand end, as was the situation with respect to the bias current directions in FIG. 4. Since the center of the transmission line is now resistive, the anti-soliton is dissipated after a time, while the soliton S reaches the selected output at the right hand side of this drawing. This provides a selection scheme which will be utilized in the switch of this invention.

In FIG. 5.2, the directions of the bias currents $I_b$ are reversed from their directions in FIG. 5.1. In this situation, the soliton will be trapped in the potential well in the center of the transmission line and will be dissipated, while the anti-soliton AS will be steered to the left in this drawing.

The structure and layout of a soliton switch using the selection principles described with respect to FIG. 4, 5.1, and 5.2 is shown in FIG. 6, while the equivalent circuit for this device is shown in FIG. 7. In more detail, strip line segment 44 is the upper electrode of an input transmission line 46, while a strip line segment 48 is the upper electrode of Josephson transmission line 50. In the same manner, strip line 52 is the upper electrode of a Josephson transmission line 54. A soliton traveling from left to right along transmission line 50 will provide the output A, while a soliton traveling to the right along output transmission line 54 will produce the voltage output B. Whether an output A or an output B will be produced depends upon the polarity of the control current $I_c$.

In more detail, transmission line 46 is comprised of a lower electrode 56, an upper electrode 44, and a tunnel barrier 58 located therebetween. The current pulse source 60 is connected to electrodes 44 and 56, and is used to generate a soliton S in transmission line 46. A bias current source 62 is connected across electrodes 44 and 56 and will provide a bias current $I_b$ across junction 58, in the direction indicated. The presence of this current will create a Lorentz force $F$ on soliton S which will cause it to move toward the U-shaped configuration comprised of transmission lines 50 and 54.

Electrode 64 is common to both transmission line 50 and transmission line 54. A tunnel barrier 66 is located between the upper and lower electrodes of transmission line 54, while a tunnel barrier 68 is located between the upper and lower electrodes of transmission line 50.

The upper and lower electrodes of all of these transmission lines are superconductors and the tunnel barriers are sufficiently thin that Josephson current can tunnel therethrough. Resistor R is located in the center of the upper electrodes 48 and 52 of the output Josephson transmission lines and is electrically isolated from the common base electrode. These output transmission lines may be viewed as a single U-shaped Josephson transmission line. Resistor R can conveniently be comprised of any normal material such as an InAu alloy in the case of Pb-In superconducting alloy electrodes. Resistor R typically is chosen to match the impedance of input transmission line 46, although it need not be precisely chosen. For example, variations from this value of 30% are acceptable. This will be apparent later when the function of the resistor R is detailed.

A control source 70 provides a control bias current $I_c$ to electrode 48. This current tunnels through barrier 68 and then travels via electrode 64 to transmission line 54. It then tunnels through barrier 66 and leaves the device via lead 72 connected to electrode 52.

The operation of the device of FIG. 6 is consistent with the principles described with respect to FIGs. 5.1 and 5.2. The soliton S which approaches the resistor R will give rise to an anti-soliton at that location, which will be dissipated. However, the soliton with the area of resistance R so quickly that it will not be dissipated. Depending upon the polarity of the control current $I_c$, it will either travel along transmission line 50 or transmission line 54. For the conventions chosen in this FIG., the soliton will provide an output A if $I_c$ is positive and will provide an output B if $I_c$ is negative. In this drawing, a soliton S is shown in transmission line 50 while a dashed line soliton S is shown in transmission line 54. Outputs A and B will be provided across the conductors shown con-
connected to the top and bottom electrodes of the output Josephson transmission lines 50 and 54.

The widths of the Josephson lines 46, 50, and 54 are less than $\lambda_J$, so that the current $I_J$ is uniform along the width. In an optimum design, the current density is adjusted to make both $\lambda_J$ and the width equal to the minimum line width that can be fabricated. The minimum length of lines 46, 50, and 54 should be at least of the order of the wavelength of a moving soliton, and can be found from numerical simulations. In order to minimize reflections, the value of the isolation resistance $R$ is chosen such that the resistance between electrode segment 44 and either of the other segments 48 and 52 is equal to the characteristic impedance of the transmission line.

The discrete resistor $R$ serves many functions, but its basic function is that of dissipating the energy of the soliton (anti-soliton) which is trapped at the potential well created along the U-shaped output transmission line. Additionally, it can have an impedance such that it will eliminate reflections of the type which are detrimental to device operation, and which are described in the Nakajima et al reference. Furthermore, the presence of resistor $R$ ensures that the control current $I_c$ will funnel from the top electrode to the bottom electrode in transmission line 50, rather than following a path along the top electrode 48 to the top electrode 52 of transmission line 54. In the embodiment of Fig. 6, the control current in transmission line 50 tunnels downward while the same current tunnels upward in transmission line 54. Because resistor $R$ prevents the control current $I_c$ from traveling back into input transmission line 46, it also provides isolation between the input stage and the U-shaped output stage of the device.

FIG. 7 is an equivalent electrical circuit of the device of FIG. 6. This equivalent circuit uses standard representations, and for this reason the transmission lines 46, 50, and 54 are represented by the inductors L and the point junctions 74. The bias current $I_b$, which flows across the tunnel junction in transmission line 46 flows along current paths represented by the point junctions 74. Resistor $R$ of FIG. 6 is represented by the resistances $R$ located between input line 46 and output transmission lines 50 and 54. Transmission lines 50 and 54 are terminated in load resistances $R_L$. The control currents $I_c$ flowing in the output transmission lines are indicated by the arrows 76.

FIG. 3 shows the well known resistively and capacitively shunted junction model which is used to represent the point junctions 74 of FIG. 7. In this model, an ideal Josephson element 78 is in parallel with the capacitor $C_q$ and a non-linear resistor $R_q$, $R_q$ is the inverse of the quasi-particle tunnelling conductance.

FIG. 9 shows a numerically calculated voltage waveform at the selected output as compared with that at the unselected output. In FIG. 9, the output voltage is plotted against time, and the selected output is represented by the solid curve 80, while unselected output is represented by the dashed curve 82. The small voltage disturbance reaching the unselected output is due to plasma oscillations and has a peak amplitude factor of 25 smaller than the selected one. Thus, the discrimination between the selected and the unselected outputs can be made very large.

In the simulation used to develop the curves of FIG. 9, Josephson transmission lines comprised of lead alloy tunnel junctions with line widths of 2.5 microns were used, where the Josephson current densities $j_J$ were 600 A/cm². The quasi-particle tunneling characteristic was chosen to be typical of that obtained with high quality junctions. The control current density used was $0.7j_J W$, where $W$ and $I$ are, respectively, the width and length of the Josephson transmission line segments. In this simulation, 24 point junction sections were used for each Josephson transmission line segment, where each segment was approximately $3 \lambda_J$ long.

In FIG. 6, the control current $I_c$ was directly coupled to the device. However, the control current $I_c$ can be magnetically coupled to the device. This is shown in FIG. 10, where the numerical designations of FIG. 6 are used wherever possible. Thus, the input transmission line 46 is connected to a U-shaped output transmission line comprising transmission line 50 and transmission line 54. The basis structure of FIG. 10 is the same as that of FIG. 6, except that the control current $I_c$ is now magnetically coupled to the device, rather than being directly injected into top electrode 48 of transmission line 50.

Magnetic coupling of the control current provides isolation of the device from the control line. It is achieved by connecting an inductor 84 between the top electrodes of lines 50 and 54, and placing a control line 86 over it. Control line 86 is insulated from the top electrodes of the transmission lines 46, 50, and 54.

In operation, a current $I_b$ through the control line induces a screening current in the device. If the screening current flows from the top electrode to the bottom electrode in transmission line 50, it will flow from the bottom electrode to the top electrode in transmission line 54. The avoid trapping a flux quantum, the design should satisfy $I_b < \Phi_0 / L$, where $L$ is the mutual inductance between the control line 86 and the inductor 84, and $I_b$ is the maximum Josephson current of a segment of the equivalent circuit. If $I_b < \Phi_0$, resetting would be required.

One of the simplest circuits that can be formed with this soliton steering device is a decoder. A two-stage tree decoder is shown schematically in the top view represented by FIG. 11. This decoder has three current steering sections at the intersections of which are located the resistors R1, R2, and R3. Depending
upon the application of control currents $I_{CA}$ and $I_{CB}$, a soliton provided to the input of Josephson transmission line 88 will appear at a selected output 1, 2, 3, or 4. An appropriate combination of the polarities of these control currents determines the output to which the soliton is delivered. For example, if $I_{CA}$ and $I_{CB}$ are positive, then output 1 is selected. If $I_{CA}$ is positive and $I_{CB}$ is negative, then output 2 will be selected. If $I_{CA}$ is negative and $I_{CB}$ is positive, output 3 will be selected. If control $I_{CA}$ is negative and control $I_{CB}$ is negative, output 4 will be selected.

The lines carrying address currents $I_{CA}$ and $I_{CB}$ can also function as address registers. In such a case, after address currents are established, decoding commences when a soliton is triggered at the input. The decoder delay is the time needed to steer a soliton from the input to the selected output. The operation of the decoder is unaffected, even if more than one soliton is generated at the input.

In the decoder of FIG. 11, the control currents are bipolar, however, by running two independent control lines (instead of one) over each steering device, unipolar currents could be used by employing a true and complement arrangement, as would be appreciated of those of skill in the art. For example, reference is made to S. M. Faris et al, IBM J. Res. Development 24, 143 (1980).

To verify the concept of the basic soliton current steering device of this invention, a circuit including a chain of 10 soliton steering devices was designed and tested. This circuit is indicated schematically in FIG. 12 and can be used to test the concept of a ten-stage decoder. Each stage of the decoder has the equivalent circuit of FIG. 7. In this experiment, the controls for the first nine stages are interconnected to a common supply current $I_{C1}$. The last stage has an independent control circuit $I_{C2}$. The pulse generator 90 at the input of the device chain includes pulse generator gate 91 and resistor R. It generates a soliton, which is accelerated through a Josephson transmission line 92 to the first stage 94. By means of the control (address) currents $I_{C1}$ and $I_{C2}$, the soliton can be steered to output 1 or output 2. The output to which the soliton is steered is determined by monitoring the voltage of the interferometer monitor gates 96 and 98 which are controlled by the output loops 100 and 102. The waveform of the current pulse associated with the soliton is sampled by a high resolution Josephson sampling scheme incorporating monitor gate 98. This sampling scheme is described by S. M. Faris in Appl. Phys. Lett. 36, 1005 (1980).

Output loops 100 and 102 contain Josephson junctions J1 and J2, respectively, which sharpen the pulses delivered to the monitor gates 96 and 98. The unselected branches of chain stages 1—9 are terminated with matching resistors (not shown in this FIG.). The circuit was designed with a five micron minimum line width technology rather than a smaller line technology, in order to increase the decoding delay for experimental convenience.

The functional operation of the chain of devices has been verified quasi-statically for all possible permutations of the inputs. The experimental Josephson current density was 250 A/cm². The tests performed are summarized in Table I with X indicating which monitor gate was switched. For example, monitor gate 96 is observed to switch only when both controls $I_{C1}$ and $I_{C2}$ are positive and a soliton is generated (device chain triggered). The range through which $I_{C1}$ and $I_{C2}$ could vary while observing the operation noted in Table 1 was measured to be ±43% for $I_{C1}$ and ±67% for $I_{C2}$. The range for $I_{C1}$ is lower than that for $I_{C2}$ because of device-to-device variation in current density. The theoretical maximum tolerance value for the range of $I_{C1}$ and $I_{C2}$ for this design is ±75%.

The pulse generator trigger T initiates a pulse 104 in the generator circuit 90. Current level 99 is the gate current for pulse generator gate 91, while current level 101 is the gate current for gate 106. Currents 103 are the gate currents for monitor gates 96 and 98.
### TABLE I

<table>
<thead>
<tr>
<th>Decoder Triggered</th>
<th>Control Polarity $I_{C1}$</th>
<th>Control Polarity $I_{C2}$</th>
<th>Output Monitor Switched</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>+</td>
<td>+</td>
<td>X</td>
</tr>
<tr>
<td>No</td>
<td>+</td>
<td>+</td>
<td>X</td>
</tr>
<tr>
<td>Yes</td>
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<td>+</td>
<td>X</td>
</tr>
<tr>
<td>No</td>
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<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Yes</td>
<td>-</td>
<td>+</td>
<td>X</td>
</tr>
</tbody>
</table>

The device delay was measured in the following manner. The current pulse 104 which triggers an input soliton also switches an interferometer 106, that functions as a delay reference gate. This gate transfers current into a reference signal line 108. This reference line is monitored by the Josephson sampler comprising monitor gate 98. After a time equal to the transit time of the soliton through the input Josephson transmission line 92, to the first stage 94, plus the total device delay, the soliton reaches the selected output. The current pulse associated with the soliton at the selected output is also monitored by the sampler comprising gate 98. From the relative separation of the two sampled waveforms, making small corrections for the trigger pulse rise time and the reference line delay, the total device delay can be extracted.

The soliton steering device of this invention can be used to provide logic circuits as was done in the aforementioned Nakajima reference. This current steering device is the fastest and smallest such device known to date and will lead to many improved circuit performances. Although specific embodiments have been shown, it will be apparent to those of skill in the art that other such embodiments can be designed. For example, multiple control lines can be used in combination where the currents in the lines add to produce the control effect, or produce opposite effects thereby effectively canceling each other. In this manner complex logic functions can be designed.

**Claims**

1. Superconducting soliton device for guiding Josephson solitons into selected transmission lines with an input Josephson transmission line (46) and at least two output Josephson transmission lines (50, 54) intersecting the input line (46) at a common intersection, these input and output lines being capable of supporting Josephson solitons therein, and with control means for steering solitons arriving at the intersection into a selected one of the output lines (50, 54), characterised in that the control means include a current source (70) for providing control currents ($I_c$) coupled simultaneously to the output lines (50, 54) through which they flow in opposite directions, these currents providing a bias at the intersection suitable for steering a soliton into the selected output line and for trapping the associated antisoliton created at the intersection, and means (R) located at the intersection for dissipating the trapped antisoliton.

2. Device as claimed in claim 1, characterised in that the means for dissipating the trapped antisoliton is a resistor (R) having a resistance such that the resistance between the input line (46) and either of the output lines (50, 54) is equal to the characteristic impedance of the input line.

3. Device as claimed in claim 1, characterised in that the control currents ($I_c$) are directly injected into the output lines (50, 54).

4. Device as claimed in claim 1, characterised in that the control currents ($I_c$) are magnetically coupled (84, 86) to the output lines (50, 54).

5. Device as claimed in claim 2, characterised in that each of the transmission lines (46, 50, 54) is comprised of first (66, 64) and (44, 48, 52) electrodes separated by a tunnel barrier (58, 68, 66) across which Josephson current can tunnel, the first electrode being
common to all transmission lines, and in that the resistor (R) is electrically connected between the second electrodes (48, 52) of the output transmission lines (50, 54).

Patentansprüche

1. Supraleitende Solitonvorrichtung zum Lenken von Josephson-Solitons in ausge-wählte Uebertragungsleitungen mit einer Eingangs-Josephson-Uebertragungsleitung (46) und wenigstens zwei Ausgangs-Josephson-Uebertragungsleitungen (50, 54), die die Eingangsleitung (46) an einem gemeinsamen Kreuzungspunkt schneiden, wobei in diesen Eingangs- und Ausgangsleitungen Josephson-Solitons auftreten können, und mit Kontroll- einrichtungen, die am Kreuzungspunkt eintreffende Solitons in eine ausgewählte Ausgangsleitung (50, 54) lenken, dadurch gekennzeichnet, dass die KontrollEinrichtungen eine Stromquelle (70) zur Lieferung von Steuerströmern (Iₚ) enthalten, die gleichzeitig an die Ausgangsleitungen (50, 54) gekoppelt werden und diese in entgegengesetzten Richtungen durchfließen, wobei diese Ströme am Kreuzungspunkt eine Vorspannung bewirken, die geeignet ist, eine Soliton in die gewählte Ausgangsleitung zu lenken und das dazugehörige, am Kreuzungspunkt entstehende Anti-Soliton dort einzufangen, und dass am Kreuzungspunkt Mittel (R) vorhanden sind, die das eingefangene Anti-Soliton auflösen.

2. Vorrichtung gemäss Anspruch 1, dadurch gekennzeichnet, dass die Mittel zur Auflösung des eingefangenen Anti-Solitons aus einem Widerstand (R) bestehen, dessen Widerstands-Wert derart ist, dass der Widerstand zwischen der Eingangsleitung (46) und jeder der Ausgangsleitungen (50, 54) gleich dem Wellenwiderstand der Eingangsleitung ist.

3. Vorrichtung gemäss Anspruch 1, dadurch gekennzeichnet, dass die Kontrollströme (Iₚ) direkt in die Ausgangsleitungen (50, 54) injiziert werden.

4. Vorrichtung gemäss Anspruch 1, dadurch gekennzeichnet, dass die Kontrollströme (Iₚ) magnetisch (84, 86) in die Ausgangsleitungen (50, 54) eingekoppelt werden.

5. Vorrichtung gemäss Anspruch 2, dadurch gekennzeichnet, dass jede der Uebertragungsleitungen (46, 50, 54) aus ersten (56, 54) und zweiten (44, 48, 52) Elektroden bestehen, die jeweils durch eine Tunnelbarriere (58, 68, 66) getrennt sind, durch welche ein Josephson-Strom tunneln kann, wobei die erste Elektrode allen Uebertragungsleitungen gemeinsam ist, und dass der Widerstand (R) elektrisch mit den zwischen Elektroden (48, 52) der Ausgangsübertragungsleitungen (50, 54) verbunden ist.

Revendications

1. Dispositif supraconducteur à solitons pour guider des solitons Josephson vers des lignes de transmission sélectionnées, comportant une ligne de transmission Josephson d’entrée (46) et au moins deux lignes de transmission Josephson de sortie (50, 54) coupant la ligne d’entrée (46) en une intersection commune, lesdites lignes d’entrée et de sortie étant capables de porter des solitons Josephson, ainsi qu’un moyen de commande pour guider les solitons arrivant à l’intersection vers une ligne sélectionnée parmi les lignes de sortie (50, 54), caractérisé en ce que le moyen de commande comprend une source de courant (70) pour fournir les courants de commande (Iₚ) appliqués simultanément aux lignes de sortie (50, 54) dans lesquelles ils passent dans des directions opposées, ces courants créant à l’intersection une polarisation appropriée pour guider un soliton vers la ligne de sortie sélectionnée et pour piéger l’antisoliton associé créé à l’intersection, ainsi qu’un moyen (R) placé à l’intersection pour dissiper l’anti-soliton piégé.

2. Dispositif selon la revendication 1, caractérisé en ce que le moyen pour dissiper l’antisoliton piégé est une résistance (R) dont la valeur ohmique est telle que la résistance entre la ligne d’entrée (46) et l’une ou l’autre des lignes de sortie (50, 54) est égale à l’impédance caractéristique de la ligne d’entrée.

3. Dispositif selon la revendication 1, caractérisé en ce que les courants de commande (Iₚ) sont injectés directement dans les lignes de sortie (50, 54).

4. Dispositif selon la revendication 1, caractérisé en ce que les courants de commande (Iₚ) sont appliqués magnétiquement (84, 86) dans les lignes de sortie (50, 54).

5. Dispositif selon la revendication 2, caractérisé en ce que chacune des lignes de transmission (46, 50, 54) est composée d’une première (56, 64) et d’une seconde (44, 48, 52) électrode, qui sont séparées par une barrière tunnel (58, 68, 66) au travers de laquelle un courant Josephson peut passer par effet tunnel, la première électrode étant commune à toutes les lignes de transmission, et en ce que la résistance (R) est connectée électriquement entre les secondes électrodes (48, 52) des lignes de transmission de sortie (50, 54).
FIG. 9

SELECTED OUTPUT

UNSELECTED OUTPUT

V (mV)

TIME (4 psec/div)