IC/87/136
INTERNAL REPORT
(Limited distribution)

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

ON THE POSSIBILITY OF THE SOLITON DESCRIPTION OF ACOUSTIC EMISSION DURING PLASTIC DEFORMATION OF CRYSTALS *

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MIRAMARE - TRIESTE
June 1987

* Submitted for publication
The essential part of this paper has been presented as a seminar during the period of the Spring College of Materials Science on Metallic Materials, ICTP, Trieste, Italy, 11 May - 19 June 1987.

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Abstract

Two basic sources of acoustic emission (AE) during plastic deformation of pure crystals are discussed. One is related to non-stationary dislocation motion (the bremsstrahlung type of acoustic radiation), and the other to dislocation annihilation processes (the main component of the transition type of acoustic radiation). The possible soliton description of the bremsstrahlung acoustic radiation by oscillating dislocation kink and by bound kink-antikink pair (dislocation breather) is considered on the basis of Eshelby's theory [Proc. Roy. Soc. London A266, 222 (1962)]. The dislocation annihilation component of transition acoustic emission is considered only in relation to the Frank-Read source operation. A soliton model for this type of acoustic radiation is proposed and the simple quantum-mechanical hypothesis is advanced for the purpose. Both soliton descriptions are discussed on the basis of available experimental data on the AE intensity behaviour during tensile deformation of crystals.

I. Introduction

There are two general approaches to explain the causes of the acoustic emission (AE) pulses generated during tensile deformation of crystals. The first one is based on the assumption that AE is induced by non-stationary dislocation motion. The theoretical fundaments for this approach were given for the first time by Eshelby[1] for an oscillating dislocation kink, and later by Kosevich[2,3] for a system of non-stationary moving dislocation loops. The AE related with a non-stationary motion of dislocations is analogous to the electromagnetic radiation by the accelerated (or/and deccelerated) charged particles, and thus this type of the AE may be called the bremsstrahlung acoustic radiation[4].

The other approach to the AE is based also on an analogy to the classical electrodynamics, i.e. the AE pulses are induced like the transition electromagnetic radiation generated by the charged particles going through the boundary between two media of different dielectric constants. Therefore the AE due to the escape of dislocations from a crystal on its free surface, being just a boundary between two elastic media of different shear modulus, may be called the transition acoustic radiation. The first theoretical analysis of this type of AE was made by Natzik at al.[5-7]. The dislocation escape from a crystal may be considered as the process of annihilation of a real dislocation with its virtual image in respect to the crystal surface. Therefore the contribution to the transition acoustic radiation (apart from the Rayleigh waves induced by the escape of edge dislocations only[7]) involves mainly the processes in which the dislocation annihilation occur, including the annihilation of dislocations inside the crystal.

The above mentioned approaches to the AE are rather of classical and phenomenological character since they are based on the continuous elastic theory and do not deal with any atomic nature of slip plane or/and dislocation motion. However, to our knowledge, the first attempt has yet been made in order to relate the slip plane with lattice dynamics[8], as well as to relate the AE with the atomic nature of dislocation motion[9], the one-dimensional Frenkel-Kontorova[10] (FK) model being used in the latter case. The FK model (including its modifications and/or extensions to higher dimensions) is still attractive for many researches on various domains of condensed matter physics, such as: dislocation dynamics (e.g. twinning processes[11], homogeneous nucleation of dislocations at high strain rates[12], thermodynamic equilibrium of kinks on a dislocation segment[13], kink motion as the soliton on a background of quasi-periodic processes[14] or kink chain dynamics[15]), commensurate-incommensurate phase transitions[16] or domain wall motion in magnetic materials[17].

In this paper, using the equivalence between soliton motion in the continuously approximated FK model and the kink motion along the dislocation line as a string in a three-dimensional crystal[18] (more recently see also [3,13-15,19]), we would like to point out some soliton and quantum-mechanical aspects of the AE induced by tensile deformation of crystals. Firstly, in Sec.II, there is proposed a simple quantum-mechanical modification of Eshelby's description of the bremsstrahlung acoustic radiation by the oscillating kink. A modification consists in the new suggestion (alternative to the one given by Eshelby[1]) on the way the kink is oscillating which follows from a soliton description of the dislocation kink behaviour. Secondly, in Sec.III, there is presented also a soliton description of the dislocation annihilation component of the transition acoustic radiation. This description is related mainly to the operation of Frank-Read source during plastic deformation since in this case over each time period when the dislocation loop runs away from the source the annihilation of the opposite sections of dislocation line occurs. A quantum-mechanical hypothesis on dislocation kink-antikink pair annihilation is advanced, and the both descriptions are discussed in Sec.IV on the basis of available experimental data.

II. The bremsstrahlung acoustic radiation by oscillating dislocation kinks

One of the mechanisms of energy dissipation during plastic deformation is related to the dislocation kink's own vibration, and the resisting force is an effect of acoustic radiation by the kink. This mechanism is sometimes called the 'flutter' mechanism[20]. Eshelby[1] proved, by means of the dislocation string model, that the rate, W, of the acoustic radiation energy due to an oscillating kink is given by

$$W = \alpha\, m_k \langle \dot{u}^2 \rangle \qquad (1)$$

where u is the linear velocity of the kink (the dot in Eq.(1) denotes the time derivative), m_k is the kink effective mass, and $\alpha = \mu a^2/10 m_k c_k^3$ depends on the quantity c_k defined as

$$c_k = c_t\left\{1 + \frac{2c_t^5}{3c_l^5}\right\}^{-1/3} \qquad (2)$$

where c_t and c_l are transversal and longitudinal velocities of the sound, respectively (μ - shear modulus, a - lattice parameter). In Eshelby's picture the kink oscillates as a whole rigid system (see Fig.1a), and the linear velocity of the kink may be written as

$$u = -\omega_k A_k \sin(\omega_k t) \qquad (3)$$

where ω_k and A_k are kink vibration frequency and amplitude, respectively.

On the other hand the previously mentioned mathematical equivalence between the one-dimensional FK soliton and the kink moving along the dislocation line as a string in the Peierls potential allows to consider the problem of internal kink vibration on the basis of the non-linear differential sine-Gordon (SG) equation

$$\frac{\partial^2\eta(x,t)}{\partial t^2} - c_o^2\frac{\partial^2\eta(x,t)}{\partial x^2} + \omega_o^2 \sin\eta(x,t) = 0 \qquad (4)$$

where c_o is the speed of sound and ω_o is the characteristic frequency. The well-known one-soliton solution of Eq.(4), given by (see e.g.[3])

$$\eta_s(x,t) = \frac{2a}{\pi}\tan^{-1}\left\{\exp\left(\frac{x - vt}{\xi}\right)\right\} \qquad (5)$$

describes the time-position dependence of the shape of one-kinked dislocation line (one end of dislocation line is located in a Peierls valley, $\eta_s=0$ for $x\to-\infty$, and the other end is located in the next Peierls valley, $\eta_s=a$ for $x\to+\infty$) in a non-dissipative sine-Gordon system where damping and external forces are disregarded. Thus, Eq.(5) describes at the same time, the only pure translational motion of the kink at v velocity along a dislocation line ($\xi = \xi_o\sqrt{1-v^2/c_o^2}$ is the kink width and $\xi_o = c_o/\omega_o$ is the kink rest width).

In a real crystal during plastic deformation the kink motion is perturbed by external force and particularly by damping force due to the thermal lattice vibration and the kink-phonon interaction should be taken into account. In this paper, however, we do not consider Eq.(4) with additional terms corresponding to the just mentioned forces. We would like to present rather a general picture of the possible kink behaviour in relation to the AE during plastic deformation which can be deduced from its pure only, but essential behaviour in a non-dissipative system. Therefore we will still use Eq.(4) and kink-phonon interaction is considered by applying Rübinstein's [21] method for a small perturbation of the SG soliton to the problem of dislocation kink internal vibration. Thus, according to Rubinstein[21], we consider a static dislocation kink, $\eta_s^o(x)=(2a/\pi)\tan^{-1}\{\exp(x/\xi_o)\}$, under a small perturbation, $\psi \ll 2a/\pi$, and we require that the function

$$\eta(x,t) = \eta_s^o(x) + \psi(x,t) \qquad (6)$$

is a solution of the SG equation. It appears that this requirement, under the assumption

$$\psi(x,t) = \psi(x)\exp(-i\omega t) \qquad (6a)$$

leads to the Schrödinger equation

$$\frac{\partial^2\psi(x)}{\partial x^2} + \frac{2M}{\hbar^2}\Big[E - V(x)\Big]\psi(x) = 0 \qquad (7)$$

which may be interpreted in the sense of de Broglie wave[22], as the one for a quasi-particle of energy $E=\hbar^2 k^2/2M$, where $k^2=(\omega^2-\omega_o^2)/c_o^2$, and of rest mass M, moving in the reflectionless potential field

$$V(x) = -\frac{\hbar^2}{M\xi_o^2}\operatorname{sech}^2(x/\xi_o) \; . \qquad (8)$$

The solution ψ_b of Eq.(7), obtained for $\omega=0$ for the first time by Landau and Lifshitz[23]

$$\psi_b(x) = 2\xi_o^{-1}\cosh^{-1}(x/\xi_o) \qquad (9)$$

describes the translational mode associated with the dislocation kink. On the other hand, the solution ψ_k, obtained for $\omega\neq 0$ for the first time by Morse and Feshbach[24]

$$\psi_k(x) = (2\pi)^{-1/2} c_o\omega^{-1}e^{ikx}\left[k + i\xi_o^{-1}\tanh(x/\xi_o)\right] \qquad (10)$$

describes the phonon modes associated with the small perturbation due to the lattice vibration see (Rubinstein[21] and more recently also Bishop at al.[25]). Thus the solution (10), taking into account the solution (9), describes the small-amplitude harmonic oscillations of the one-kinked dislocation line. It should be emphasized here that also the large-amplitude anharmonic oscillations of the one-kinked dislocation line have been discussed[14] using the mixed, one-soliton one-periodic solution of the SG equation found recently by Zagrodzinski and Jaworski[26]. It has been shown there[14] that the anharmonic dislocation line vibrations are due to the excitation and propagation of 'heavy' rather than normal phonons along dislocation line. The 'heavy' phonons, introduced by Eshelby[1] and later discussed also by Seeger and Engelke[20], are responsible according to Eshelby for a short-range interaction between the kinks on the dislocation line. Moreover, the mixed one-soliton one-periodic solution of the SG equation, describing anharmonic oscillations of the one-kinked dislocation line is a more general one because it tends, in low-amplitude limit, just to Rubinstein's solution given by (10) for harmonic oscillations - as it has been recently shown analytically by Jaworski[27]. Therefore in both harmonic and anharmonic cases the dislocation line vibration are due to the excitation of the 'heavy' phonon modes[14] since even in a harmonic case the dispersion relation for the phonons is still $\omega^2=c_o^2k^2+\omega_o^2$. Below we show that the kink besides its translational motion along dislocation line, has also its own internal oscillation originating by its interaction with 'heavy' phonons.

The reflectionless character of V(x) potential means that it is transparent for 'heavy' phonon modes, i.e. $\psi(x)$ does not change their dispersion relation $\omega^2=c_o^2k^2+\omega_o^2$, except the ψ_o mode of ω_o frequency and of k=0 wave vector which is trapped by the soliton at rest. This means that the static kink vibrates at the same ω_o frequency as one the modes just trapped by it. However, the way the kink is oscillating is rather different than the one discussed by Eshelby[1]. It follows from the forms of the translational mode ψ_b given by (9), and of the vibrational mode ψ_o, given by (10) for k=0, and particularly from Eq.(6a). Moreover, from Eq.(8) follows that the increment of atom displacement $\Delta\eta_s^o$ for a static kink

$$\Delta\eta_s^o = \frac{\partial\eta_s^o}{\partial x}\Delta x = \frac{a}{\pi\xi_o}\psi_b\Delta x \qquad (11)$$

is determined by the kink one-dimensional compressive or tensile strain $\partial\eta_s^o/\partial x$ which is related just with the ψ_b magnitude. Consider the screw dislocation line with a static kink. In this case the kink is of the character of edge dislocation line section, and the 'heavy' phonon modes should be of a longitudinal polarisation, i.e. along the dislocation line. Thus we may say that dislocation kink own internal oscillations, responsible for acoustic radiation, consist in the successive tensile and compressive strain occurring at the ω_o frequency and with an amplitude $A_o(\psi_o)$ depending on the ψ_o magnitude (see Fig. 1b or 1c). Although Eshelby's formula (1) is of a classical character, we assume that it is still valid, however, instead of u in Eq.(3) we should use the linear velocity u_o of the static kink in its compressive-tensile oscillating motion

$$u_o = -\omega_o A_o(\psi_o)\sin(\omega_o t). \qquad (12)$$

The considerations presented above are valid also for a translatory motion of the dislocation kink since, according to Rubinstein[21], the SG equation is invariant with respect to the Lorentz transformation. It should be noticed here that the more exact proof for a moving SG soliton has recently been given by Fernandez at al.[28]. Using also the Rubinstein[21] method for a small perturbation and applying the Lorentz transformation they have shown that the soliton of the SG equation behaves just like a quasi-particle in the sense of de Broglie wave since its momentum in a moving coordinate system at v velocity is proportional to the wave vector $k=\xi_o^{-1}(v/c_o)/\sqrt{1-v^2/c_o^2}$ of the vibrational mode just trapped by the translatory moving soliton. Thus the total linear velocity of the moving dislocation kink varies within the range of $v\pm u_m$, where only the term u_m is responsible for acoustic radiation. And similarly to the Eq.(12) the velocity u_m may be written as

$$u_m = -\omega_m A_m(\psi_k)\sin(\omega_m t) \qquad (13)$$

where $\omega_m^2 = c_o^2k^2+\omega_o^2$ and the amplitude A_m depends on ψ_k which is given by (10) for $k=\xi_o^{-1}(v/c_o)/\sqrt{1-v^2/c_o^2}$.

It is interesting that, at the same time, Ens[29] suggested that the breather (so is called the oscillating bound soliton-antisolito pair) of the SG equation behaves also like a quasi-particle in the sense of de Broglie wave since its momentum and energy are proportional to its wave vector and vibration frequency, respectively. Applying his idea to the dislocations we may suppose that in a real crystal dislocation breathers can exist which, being the bound dislocation kink-antikink pairs, have their own internal oscillations too (see Fig.2). Thus the dislocation breather, η_b, is also described by the well-known two--soliton SG equation solution which may be written in a similar form as used by Ens[29]

$$\eta_b(x,t) = \frac{a}{2\pi}\tan^{-1}\left\{\frac{s\sin\left[r\cdot\frac{c_o t-(v/c_o)x}{\xi_o}\right]}{r\cosh\left(s\cdot\frac{x-vt}{\xi_o}\right)}\right\} \qquad (14)$$

where $s = \sin q$, $r = \cos(q)$, q is a constant, and the breather frequency ω_b, for a small parameter $r \ll 1$, may be written as follows

$$\omega_b = \frac{2c_o}{\xi}\exp\left(-\frac{A_b}{2\xi}\right) \qquad (15)$$

where A_b is the amplitude of breather frequency and v is its velocity as a whole system. Hence, the dislocation breather, again by analogy to the oscillating charged particle in electrodynamics, can also produce the bremsstrahlung type of acoustic radiation. Thus, in the case of dislocation breather, similarly to Eqs(12) and (13), the component u_b of its total linear velocity, responsible for this radiation can be written as

$$u_b = -\omega_b A_b \sin(\omega_b t)\,. \qquad (16)$$

Eventually, the way the dislocation breather is oscillating (see Fig.2) is a very strong support for the way proposed in this paper for the single kink oscillations because in both cases the oscillations are related rather to the changes in kinks width than to the changes in positions of the kink system as a whole.

III. The soliton mechanism of the AE due to the Frank-Read source operation

It is the well-known fact that a dislocation segment can act during the plastic deformation as a Frank-Read source, and that in every stage of the source operation, associated

with a generation of successive dislocation loop the sections of the dislocation line of opposite orientations are annihilated. In this sense the Frank-Read source is, at the same time, also the source of the transition type of acoustic radiation. Of course, it is also the source of bremsstrahlung acoustic radiation because of an acceleration of dislocation loops generated from it. The latter case was discussed by Natsik and Chishko[30] and the former one recently also by Pawelek at al.[4,31]. Here we would like to show a possible soliton mechanism of the dislocation line section annihilation during a Frank-Read source operation. We give, however, only general picture and we consider the simplest case of the annihilation process of two dislocation kinks of opposite signs. In a completly pure case the annihilation process of the dislocation kink-antikink pair is quite well described by the soliton-antisoliton dublet $s\text{-}\bar{s}$, being an other well-known two-soliton solution of the SG equation (see e.g. [21])

$$\eta_{s\bar{s}}(x,t) = \frac{2a}{\pi}\tan^{-1}\left\{\frac{c_o\sinh(vt/\xi)}{v\cosh(x/\xi)}\right\}. \qquad (17)$$

Fig.3 shows the interaction between the kink and the antikink both moving along the dislocation line at the same velocity v but in opposite directions. It should be emphasized that Eq.(17) describes the dislocation kink-antikink pair annihilation process in a completely non-dissipative sine-Gordon system, and thus this process leads at once to the creation of new kink-antikink pair running away along a dislocation line in opposite directions and at the same velocities as before the annihilation. However, the kinks now move in another Peierls valley which is shifted by two interatomic distances (Fig.3). Such a mechanism, as well as the formation of completely new kinks with the aid of thermal fluctuations can serve as a quite possible way for the forward motion of dislocations in active slip planes under an external shear stress during plastic flow (see Fig.4). It is clear that both of these mechanisms (creation of thermal kinks and the annihilation of kink pairs with their simultaneous creation, Fig.4) occur on the same dislocation line.

However, the Frank-Read source operation involves an additional mechanism. The motion of approaching each others dislocation line sections can also lead merely to the kink-antikink pair annihilation processes without simultaneous creation of new kink pairs because each kink of an annihilating pair belongs to different sections of dislocation line. Fig.5 illustrates schematically the soliton mechanism of such an annihilation process. It has been assumed here that the initial segment AB is an edge dislocation (Fig.5a). In this case the approaching sections A_1A_2 and B_1B_2 of the dislocation line (Fig.5b) are the same as the screw dislocations of opposite signs. When assuming that the axis x passes along a section e.g. A_1A_2, one can see that the positive edge kinks on the A_1A_2 section are solitons (s) since they do move along x axis, whereas similar kinks on the B_1B_2 section are antisolitons ($\bar{s}$) since they do move in opposite direction to x axis (see Fig.5c). When A_1A_2 and B_1B_2 sections are approaching one another (on the distance of one or few spacings between the Peierls valleys) their soliton configuration (Fig.5c) changes rapidly due to the annihilation of soliton-antisoliton pairs. As it has been pointed out previously it is quite evident that there are annihilated mostly such kink pairs where one soliton belongs to the A_1A_2 section and the other to the B_1B_2 section. Consequently, these sections do completely disappear (Fig.5d). The scheme of the mechanism of such a disappearance (see Fig.5e) illustrates the simplest case only (for better clearness of the drawing), when the approaching dislocation sections are rectalinear (both of A_1A_2 ends lie in a Peierls valley and both of B_1B_2 in next one) and on each of these sections is a single s-$\bar{s}$ pair only. Thus Fig.5e illustrates an elementary process of the dislocation kink--antikink pair annihilation during the Frank-Read source operation. Therefore, assuming that the kink behaves like a quasi-particle, as it has been arguated in Sec.II, we suppose that the most probable effect of dislocation kink pair annihilation is the creation of two quanta of elastic wave (quite analogously to electron-positron pair annihilation resulting mostly in the creation of two photons). Denote the kink and antikink energies by E_s and $E_{\bar{s}}$ respectively. Then during the disappearance of the rectangular $A_1'A_2'B_1'B_2'$ loop (Fig.5e) two translational modes associated with solitons must disappear which should result most probably, in the creation of two phonons of ω frequency. This fact may be written schematically as follows

$$E_s + E_{\bar{s}} = 2\hbar\omega. \tag{18}$$

Thus, it is seen that during Frank-Read source operation rather a multisoliton annihilation process occurs which is very efficient and abundant source of phonons production. Below we discuss both approaches to AE on the basis of available experimental data.

IV. Discussion

The bremsstrahlung type of acoustic radiation induced by the oscillating system of dislocation kinks (single kink or dislocation breather), considered in this paper on the basis of Eshelby's theory, is rather of high frequency character. On the contrary, similar types of acoustic radiation induced by the system of non-stationary moving dislocation loops discussed by Kosevich[2,3], are rather of low frequency character. This is because in the former case the AE is related to atom vibrations whereas in the latter one it is rather related to macroscopic sizes of dislocation loop system.

On the one hand, the most experimental observations of AE during plastic deformation of crystals are interpreted in relation to the non-stationary motion of dislocations though not always referred to directly to any of the above mentioned theories. For instance, Fisher and Lally[32] suggested that AE is a consequence of the fast collective motion of a large number of dislocations. Similarly Sedgwick[33] has considered the operation of the fast dislocation sources or the sudden release of dislocation pile-ups as possible AE sources. He stated that there exist a correlation between the sizes of dislocation sources (i.e. lengths of dislocation segments being potential Frank-Read sources) and the observed distribution of the measured AE intensity as a strain function. Another explanation was given by James and Carpenter[34] who suggested that the observed AE pulse rate is proportional to the rate of the mobile dislocation density increase which is imposed by the stimulating processes of the dislocation breakaway from the pinning points and, in turn, to a less degree by the fast multiplication of dislocations. Thus, these explanations assumed, in a certain sense à priori, the bremsstrahlung type of acoustic radiation as the main contribution to the observed AE signals.

On the other hand, the series of experiments on calcite crystals carried out by Boiko at al.[35,36] strongly suggest that the main contribution to the observed AE signals arises rather from the dislocation annihilation component of the transition type of acoustic radiation. Such a suggestion is supported by the fact that they have not observed[36] any essential changes in AE intensity during only non-stationary motion of dislocations, i.e. the AE intensity before the escape of dislocations from a crystal was considerably lower than just during their escape. Also our recent experimental results[4,31] are in good qualitative agreement with the explanation of AE in terms of transition type of acoustic radiation. Namely, it has been stated[4] that the increase of AE intensity induced by the sudden change in strain rate during copper single crystal tensile deformation is caused by the increase of dislocation line section annihilation events due to the generation of dislocation loops emitted from additional number of Frank-Read sources, started just owing to the strain rate increase. Also other correlation between the behaviour of AE and mechanisms of plastic flow of copper single crystals during two first stages of work-hardening has recently been reported[31]. There was also stated there[31], among others, that there exists also the correlation of AE intensity distribution with Frank-Read source length distribution (i.e. similarly was suggested by Sedgwick[33]), however, not immediate, but rather through the distribution of dislocation line section annihilation events, determined just by the Frank-Read source distribution.

As a final conclusion one can say that the soliton description of the bremsstrahlung type of acoustic radiation by the oscillating dislocation kink or breather, as well as the soliton description of the dislocation annihilation component of transition acoustic radiation due to the Frank-Read source operation may be useful in practice for the determination of the contribution of both types of radiation to the observed AE signals. Hence, the possibility of the soliton and simple quantum-mechanical description of the acoustic radiation may be helpful in an exact spectral analysis of the AE pulses generated during plastic deformation.

ACKNOWLEDGEMENTS

The author would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste. He would also like to thank Professor G. Caglioti for his general remark on this paper.

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Figures captions

Fig.1. Schematic illustraiions of the dislocation kink internal oscillations after Eshelby[1] (a) and according to soliton description (b,c).

Fig.2. Schematic illustration of the internal scillations of the dislocation breather moving as a whole at v velocity along a dislocation line parallel to the x-axis.

Fig.3. Schematic representation of the dislocation kink-antikink pair annihilation with instantaneous creation of new kink-antikink pair.

Fig.4. Schematic representation of the forward motion of dislocation under external shear stress as a result of both kink-antikink pair formation with aid of thermal fluctuation (e.g. $s_i-\bar{s}_i$ pairs where i=1,..,6), and with of their earlier annihilation (e.g. $s_1-\bar{s}_3$, $s_4-\bar{s}_1$ pairs).

Fig.5. Soliton mechanism of dislocation section annihilation during dislocation loop generation by Frank-Read source (for details see in the text).

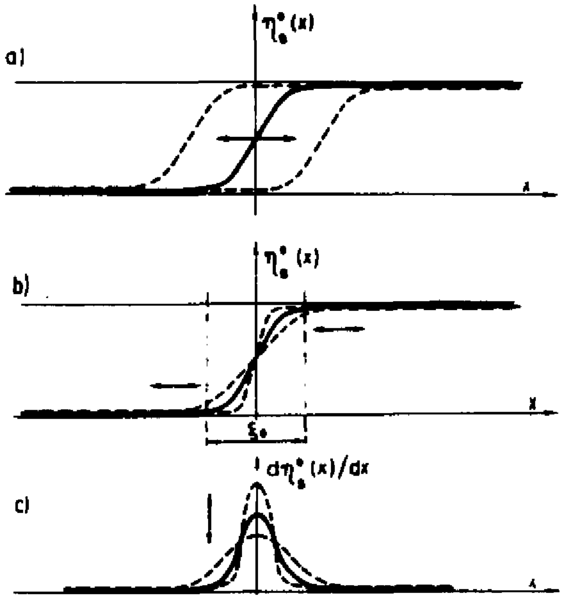

Fig.1

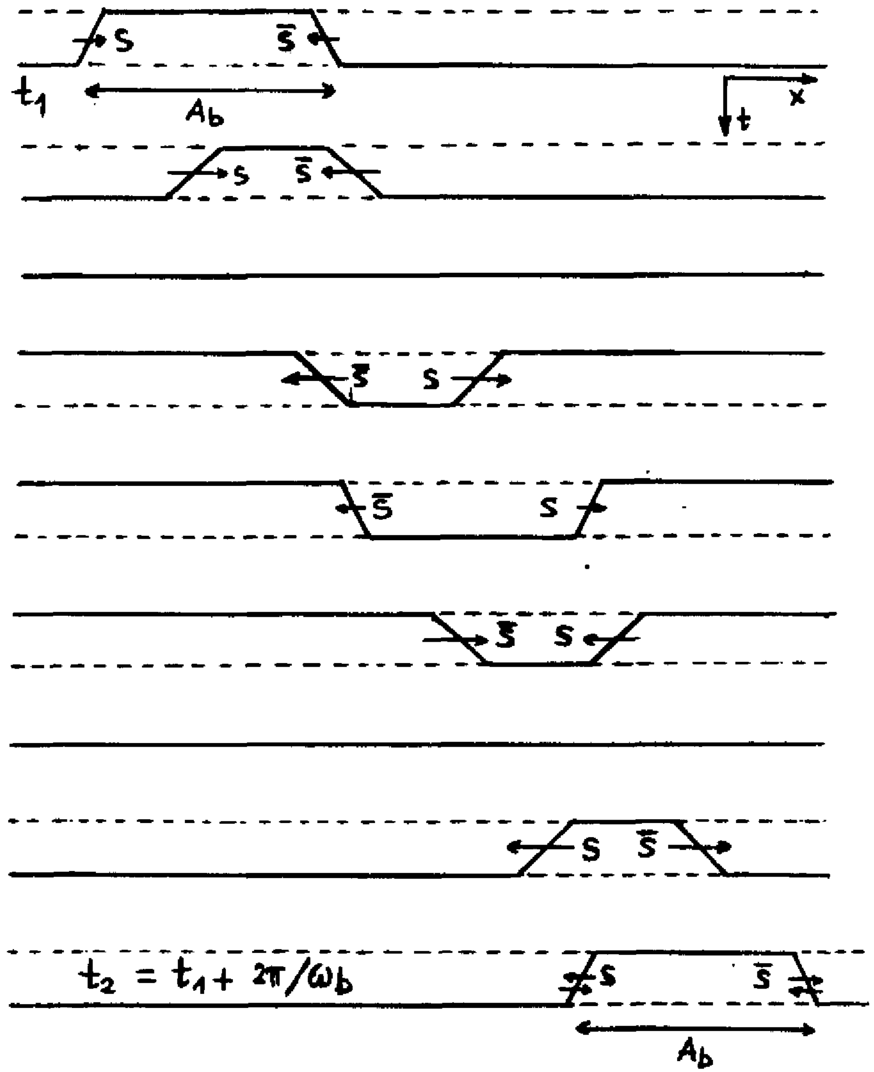

Fig.2

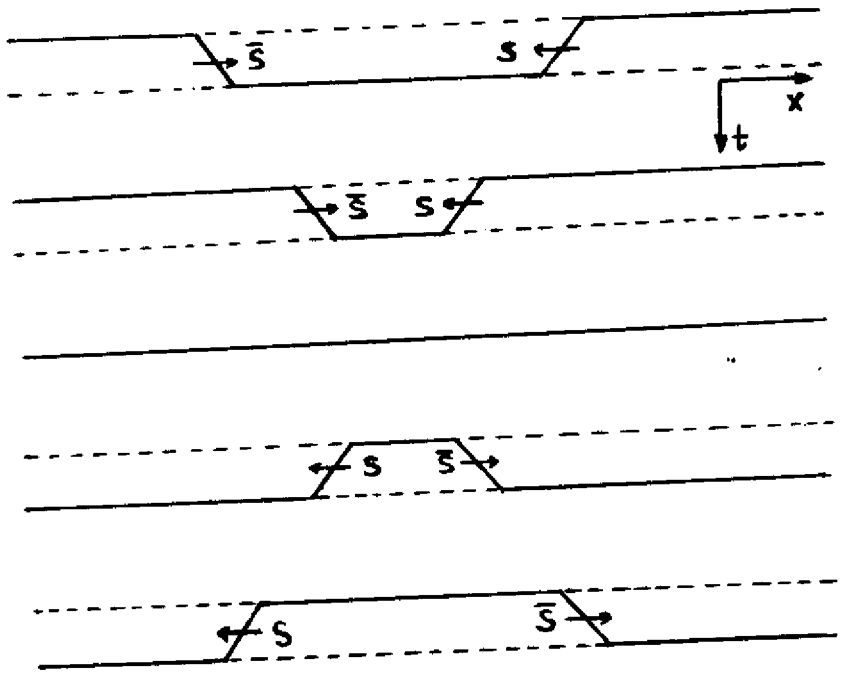
S̄
S
x
t

Fig.3

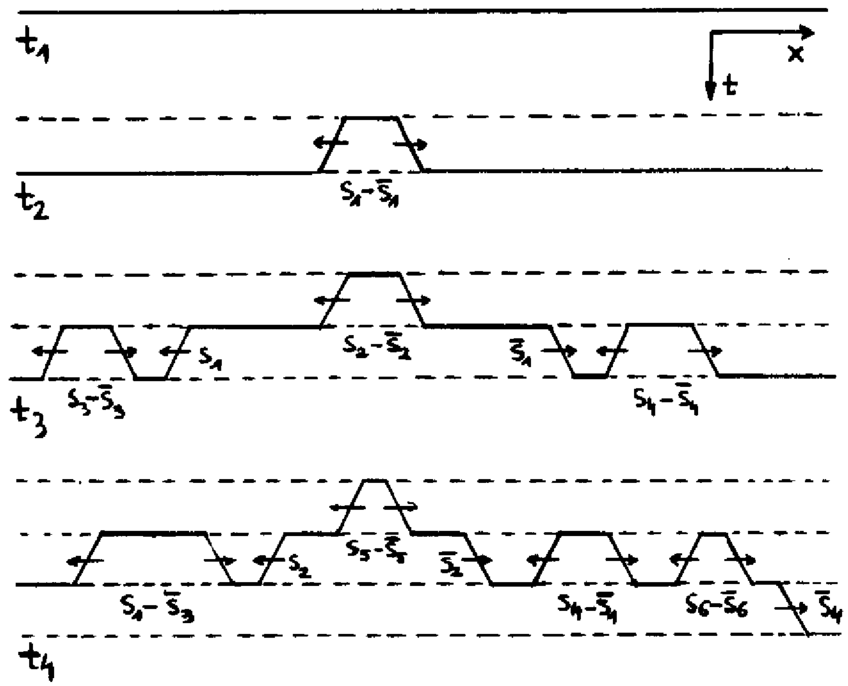
t_1
x
t
t_2
$S_1-\bar{S}_1$
t_3
S_1
$S_2-\bar{S}_2$
$\bar{S}_1$
$S_3-\bar{S}_3$
$S_4-\bar{S}_4$
$S_5-\bar{S}_5$
S_2
$\bar{S}_2$
$S_1-\bar{S}_3$
$S_4-\bar{S}_1$
$S_6-\bar{S}_6$
$\bar{S}_4$
t_4

Fig.4

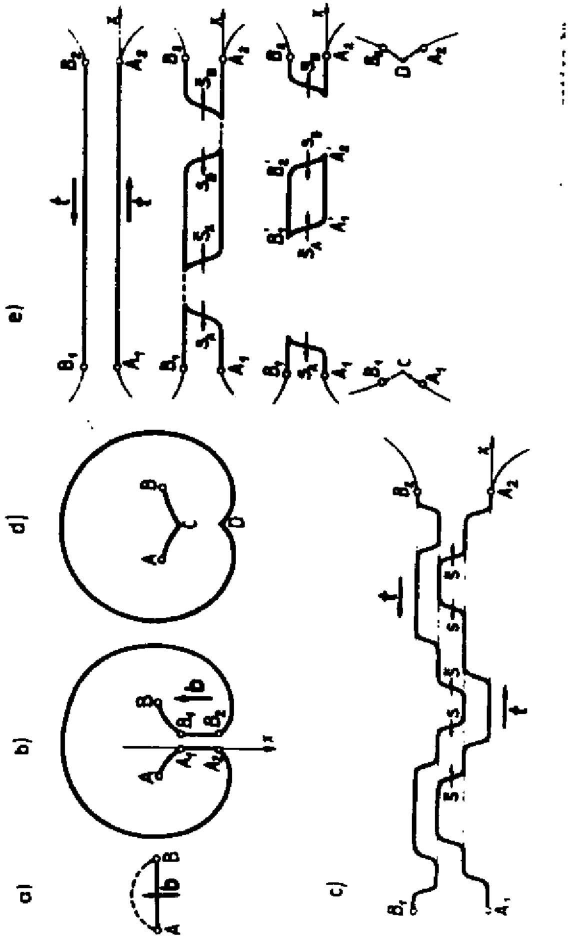

Fig.5