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Gluon Green function in axial gauge

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***Abstract**:*
Proposed by V.Ya. Fainberg et al. "Yang-Mills Field Quantization InModified Axial Gauge" is advanced and gluon Green function in a modified axial gauge is calculated. Green function evaluation in these gauges is not based on the theory of perturbations. The calculation results in a simple algebraic system of the equations and this system allows one to calculate Green function in these gauge. We found an expressions, which is in a good accordance with the results of earlier works.

***Keywords**: Axial gauge, gluon propagator*

Since the works by Schwinger [1] and Fradkin [2] an axial gauge $n_\mu A_\mu = 0$ (in particular $A_0 = 0$) in gauge theories began intensively be investigated. These gauges possess a serious of attractive features: there are no ghost-fields in them, that in particular simplifies Ward's identities and allows to hope for obtaining the 'closed' equations only for fermions and gauge fields [3]- [12], secondly, the presence of residual symmetry enables to take into account non trivial topological configurations [13], on canonical quantization. Also, the light-cone gauge $n^2 = 0$ is the most convenient in connection with quantization of supersymmetric Yang-Mills theories [14]. But on the other hand, the big 'residual' symmetry in gauge $n_\mu A_\mu = 0$ appearing at canonical quantization in non-renormalizable of the physical vectors state satisfying Gauss law, in occurrence of ambiguities at avoid of poles of $1/(nk)$ in of propagating function of gauge particles. One of ways definition avoid of these poles is introducing of arbitrary rule for avoiding, i.e. introduction definition expressions with a pole as a limit at $\varepsilon \to 0$ analytical function [15]. In particular, to this problem are devoted serious of works of A.A. Khelashvili et al. [6], [9]-[10]. Particulary, in [6] using the Delbourgo representation [15] for the three-gluon vertex function as the solution of the Slavnov-Taylor identity, it is shown that the Dyson-Schwinger equation for the gluon propagator in the axial gauge reduces to the linear integral equation for the spectral density. By means of going to the light-like gauge the explicit form of this equation is derived the solution of which has the same behavior in both the ultraviolet and infrared regions, in distinction with [15]. It is possible, the approaches for avoidance of poles of $1/(nk)$ in the $A_0 = 0$ gauge, by obtaining the propagator for 'longitudinal' gluon which could describe transition between the physical vectors satisfying Gauss law [16].

For avoidance of the above mentioned poles, in the spirit of the works [9],[17], by means of modification of the gauge condition $A_0 = 0$ the residual gauge degrees of freedom temporarily are frozen that after all calculations and the frosts parameter are sent to zero [18]. Thus some advantages of $n_\mu A_\mu = 0$ gauges are saved.

It should remark some works which appeared later: review by R.Alkofer [19] and references therein.

In work [18] by V.Ya. Fainberg et al. the gauge $t_\mu = n_\mu + i\varepsilon \frac{k_\mu}{k^2}$ was proposed and the Green function was found. Here ε is a constant and has dimension $[k]$ and, the gauge is named as the generalized axial gauge.

In present article we propose scheme for calculation of the Green function in the generalized axial gauge like $t_\mu = n_\mu + i\varepsilon \frac{k_\mu}{k^2} - i\varepsilon \frac{(nk)n_\mu}{k^2}$ and compute the Green function in this gauge.

Let us write down Lagrangian of the gauge field

$$L = \frac{1}{4}(F^a_{\mu\nu})^2 + \frac{1}{2\alpha}F^2(A) = -\frac{1}{4}(F^a_{\mu\nu})^2 + \frac{1}{2\alpha}t_\mu(k)A_\mu \cdot t^*_\nu(-k)A_\nu \qquad (1)$$

where $F^a_{\mu\nu} = \frac{\partial A^a_\mu}{\partial x_\nu} - \frac{\partial A^a_\nu}{\partial x_\mu}$, $F(A)$ is a function fixing the gauge and t_μ is some integer-differential operator.

Because the Lagrangian is a real function, we conclude, that $t_\mu(k) = t^*_\nu(-k)$ is unique vectors in Euclidian space, and we can choose $n^2_\mu = 1$. Equation for gluon field can be obtained by varying the Lagrangian (1):

$$[(\Box\delta_{\mu\nu} - \partial_\mu\partial_\nu + \frac{1}{\alpha}t_\mu(k)t^*_\nu(-k)f(\Box)]A_\mu(x) = 0$$

and for the Green function we find in momentum space the following expression:

$$[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} - \frac{1}{\alpha}\frac{t_\mu(k)t^*_\nu(-k)}{k^2}f(\Box)]G_{\nu s}(x) = -\frac{\delta_{\mu s}}{k^2} \qquad (2)$$

Here $f(\Box)$ is introduced for maintenance of dimensionless of the third term. Choosing $f(\Box) = \Box$ in the momentum space, we get the following equation

$$[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} + \frac{1}{\alpha}t_\mu(k)t^*_\nu(-k)]G_{\nu s} = -\frac{\delta_{\mu s}}{k^2} \qquad (3)$$

Substituting t_μ into (3) we obtain the functional equation for definition of the gluon Green function

$$\left[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} + \frac{1}{\alpha}\left(n_\mu + i\varepsilon\frac{k_\mu - (nk)n_\mu}{k^2}\right)\left(n_\nu + i\varepsilon\frac{k_\nu - (nk)n_\nu}{k^2}\right)\right]G_{\nu s} = -\frac{\delta_{\mu s}}{k^2} \ . \qquad (4)$$

Having solved the functional equation (4) we can determine gluon Green function. We shall not solve the equation (3) but determine gluon Green function employing the following scheme. The analysis of Eq.(4) reveals that gluon Green function has the tensor structure:

$$G_{\nu s} = \beta_1\delta_{\nu s} + \beta_2 k_\nu k_s + \beta_3 n_\nu n_s + \beta_4(n_\nu k_s + n_s k_\nu) \ . \qquad (5)$$

Multiplying Eq.(5) by $k_\nu k_s$, $\delta_{\nu s}$, $n_\nu n_s$ and $n_\nu k_s$ we get the following system of the algebraic equations:

$$\begin{cases} \delta_{\nu s} G_{\nu s} = 4\beta_1 + k^2\beta_2 + \beta_3 + 2(nk)\beta_4 \\ k_\nu k_s G_{\nu s} = k^2\beta_1 + k^4\beta_2 + (nk)^2\beta_3 + 2k^2(nk)\beta_4 \\ n_\mu n_s G_{\nu s} = \beta_1 + (nk)^2\beta_2 + \beta_3 + 2(nk)\beta_4 \\ k_\nu n_s G_{\nu s} = (nk)\beta_1 + k^2(nk)\beta_2 + (nk)\beta_3 + (k^2 + (nk)^2)\beta_4 \end{cases} . \qquad (6)$$

To define the right part of the system (6) we multiply Eq. (4) by k_μ and n_μ obtain the following system:

$$\begin{cases} \left(n_\nu + i\varepsilon \frac{k_\nu}{k^2} - i\varepsilon \frac{(nk)n_\nu}{k^2} \right) G_{\nu s} = -\frac{\alpha k_s}{k^2} \cdot \frac{1}{(nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)} \\ \left(n_\nu - \frac{(nk)k_\nu}{k^2} \right) G_{\nu s} = -\frac{n_s}{k^2} + \frac{k_s}{k^2} \cdot \frac{1}{(nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)} \end{cases} \qquad (7)$$

Having solved the system (7) we find

$$n_\nu n_s G_{\nu s} = -\frac{(nk)^2}{k^2} \cdot \frac{1}{\left((nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)\right)^2} \left(\alpha - \frac{\varepsilon^2}{(nk)^2}\left(1 - \frac{(nk)^2}{k^2}\right)\right)$$

$$n_\nu k_s G_{\nu s} = -\frac{(nk)}{\left((nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)\right)^2} \left(\alpha - \frac{\varepsilon^2}{k^2}\left(1 - \frac{(nk)^2}{k^2}\right)\right)$$

$$k_\nu k_s G_{\nu s} = -1 - \frac{k^2}{\left((nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)\right)^2} \left(1 + \alpha - \frac{\varepsilon^2}{k^2}\left(1 - \frac{(nk)^2}{k^2}\right)\right)$$

and $\delta_{\nu s} G_{\nu s}$ is determined by multiplying the equation (4) on $\delta_{\mu s}$, which results in the equality

$$\delta_{\nu s} G_{\nu s} = -\frac{2}{k^2} - \frac{1}{\left((nk) + i\varepsilon\left(1 - \frac{(nk)^2}{k^2}\right)\right)^2} \left(1 + \alpha - \frac{\varepsilon^2}{k^2}\left(1 - \frac{(nk)^2}{k^2}\right)\right).$$

Thus the system (6) can be rewrite in the following form:

$$\begin{cases} 4\beta_1 + k^2\beta_2 + \beta_3 + 2\beta_4(nk) = -\frac{2}{k^2} - \frac{1}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(1+\alpha-\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right) \\ k^2\beta_1 + k^4\beta_2 + \beta_3(nk)^2 + 2\beta_4 k^2(nk) = 1 - \frac{k^2}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(1+\alpha-\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right) \\ \beta_1 + 1k^2\beta_2 + \beta_3 + 2\beta_4(nk) = -\frac{(nk)^2}{k^2}\cdot\frac{1}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(\alpha-\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right) \\ \beta_1(nk) + \beta_2 k^2(nk) + \beta_3(nk) + \beta_4\left(k^2+(nk)^2\right) = -\frac{(nk)}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(\alpha-\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right) \end{cases} \tag{8}$$

Solving the system (8) we get the following values:

$$\beta_1 = -\frac{1}{k^2}; \qquad \beta_2 = -\frac{1}{k^2\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(1+\alpha+\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right);$$

$$\beta_3 = 0; \qquad \beta_4 = -\frac{(nk)}{k^2}\cdot\frac{1}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2};$$

Thus for gluon Green function we find the formula:

$$G_{\nu s} = -\frac{1}{k^2}\left\{ \delta_{\nu s} + \frac{k_\nu k_s}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2}\left(1+\alpha+\frac{\varepsilon^2}{k^2}\left(1-\frac{(nk)^2}{k^2}\right)\right) - \right.$$

$$\left. -\left(k_\nu n_s + k_s n_\nu\right)\frac{(nk)}{\left((nk)+i\varepsilon\left(1-\frac{(nk)^2}{k^2}\right)\right)^2} \right\}; \tag{9}$$

This formula is the gluon Green function in the gauge - $t_\mu = n_\mu + i\varepsilon \frac{k_\mu}{k^2} - i\varepsilon \frac{(nk)n_\mu}{k^2}$; and at $\frac{(nk)^2}{k^2} \to 0$ rightarrow -coincides with the result of work [18], and at $\varepsilon \to 0$; we recover the results of the works [3], [4], [8]-[10], [11], [12], [20]. It is worth to note that at $\varepsilon = \frac{i(nk)}{1-\frac{(nk)^2}{k^2}}$ the formula (9) has a pole. It is a simple pole and the rule for avoiding this pole is usual, and it should be noted that this pole dapper, that is depending on the value of $\frac{(nk)^2}{k^2}$ pole is displaced to the right.

In the work [20] the gauge vector was introduced and demonstrated that the gluon Green function is perpendicular to the gauge. The formula (6) at $\alpha = 0$ and $\varepsilon \to 0$ is perpendicular to an unit vector in the Euclidean space

$$n_\mu G_{\mu\nu} = n_\nu G_{\mu\nu} = 0$$

Hence, the gauge and unit vectors in the Euclidean space have the same direction. Now we shall consider the generalized axial gauge of the following form:

$$t_\mu = n_\mu + \frac{i\varepsilon k_\mu}{(k_\mu - (nk)n_\mu)^2} - \frac{i\varepsilon n_\mu (nk)}{(k_\mu - (nk)n_\mu)^2}$$

Substituting t_μ to in the equation (2) we find:

$$\left[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} + \frac{1}{\alpha}\left(n_\mu + i\varepsilon \frac{k_\mu - (nk)n_\mu}{k^2 - (nk)^2}\right)\left(n_\nu + i\varepsilon \frac{k_\nu - (nk)n_\nu}{k^2 - (nk)^2}\right)\right] G_{\nu s} = -\frac{\delta_{\mu s}}{k^2}$$

The analysis of this equation shows that its structure can be presented just as in Eq.(5).

Repeating the offered order of operations described above, get the system of the algebraic equations similar to (6):

$$n_\nu n_s G_{\nu s} = -\frac{(nk)^2}{k^2} \cdot \frac{1}{((nk) + i\varepsilon)^2} \left\{ \alpha - \frac{\varepsilon^2}{(nk)^2 \left(1 - \frac{(nk)^2}{k^2}\right)} \right\}$$

$$n_\nu k_s G_{\nu s} = -\frac{(nk)}{((nk) + i\varepsilon)^2} \left\{ \alpha - \frac{\varepsilon^2}{k^2 \left(1 - \frac{(nk)^2}{k^2}\right)} \right\}$$

$$k_\nu k_s G_{\nu s} = -1 - \frac{k^2}{\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha - \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\}$$

$$\delta_{\nu s} G_{\nu s} = -\frac{2}{k^2} - \frac{1}{\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha - \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\}$$

Thus, it is necessary to solve the following system of the algebraic equations:

$$\begin{cases} 4\beta_1 + k^2\beta_2 + \beta_3 + 2\beta_4 (nk) = -\frac{2}{k^2} - \frac{1}{\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha - \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\} \\ k^2\beta_1 + k^4\beta_2 + \beta_3 (nk)^2 + 2\beta_4 k^2 (nk) = 1 - \frac{k^2}{\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha - \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\} \\ \beta_1 + 1k^2\beta_2 + \beta_3 + 2\beta_4 (nk) = -\frac{(nk)^2}{k^2}\cdot\frac{1}{\left((nk)+i\varepsilon\right)^2}\left\{ \alpha - \frac{\varepsilon^2}{(nk)^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\} \\ \beta_1 (nk) + \beta_2 k^2 (nk) + \beta_3 (nk) + \beta_4\left(k^2 + (nk)^2\right) = -\frac{(nk)}{\left((nk)+i\varepsilon\right)^2}\left\{ \alpha - \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\} \end{cases}$$

Solution of this system has the form:

$$\beta_1 = -\frac{1}{k^2}; \qquad \beta_2 = -\frac{1}{k^2\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha + \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\}$$

$$\beta_3 = 0; \qquad \beta_4 = -\frac{(nk)}{k^2}\cdot\frac{1}{\left((nk)+i\varepsilon\right)^2};$$

and the gluon Green function is given by the equation:

$$G_{\nu s} = -\frac{1}{k^2}\left\{ \delta_{\nu s} + \frac{k_\nu k_s}{\left((nk)+i\varepsilon\right)^2}\left\{ 1+\alpha + \frac{\varepsilon^2}{k^2\left(1-\frac{(nk)^2}{k^2}\right)} \right\} - \right.$$

$$\left. -\left(k_\nu n_s + k_s n_\nu\right)\frac{(nk)}{\left((nk)+i\varepsilon\right)^2} \right\} \tag{10}$$

The formula (10) has the pole at the point---. This pole is shifted towards values ----a pole of the formula(8). Here transversity of the Green function to the unit vector in the Euclidean space is also satisfied.

Now we shall consider the following modified axial gauge:

$$t_\mu A_\mu = \left(n_\mu + \frac{\varepsilon^2 k_\mu}{k^2 (nk)} \right) A_\mu$$

Substituting value t_μ in the equation (2) and choosing, $f(\Box)=\Box \Rightarrow -k^2$ we get the following functional equation for definition of $G_{\nu s}$ in the form:

$$\left[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} + \frac{1}{\alpha} \left(n_\mu + \varepsilon^2 \frac{k_\mu}{k^2 (nk)} \right) \left(n_\nu + \varepsilon^2 \frac{k_\nu}{k^2 (nk)} \right) \right] G_{\nu s} = -\frac{\delta_{\mu s}}{k^2} \tag{11}$$

We multiply this equation on k_μ and then on n_μ and find the following equations:

$$\begin{cases} \left(n_\nu - \frac{(nk) k_\nu}{k^2} \right) G_{\nu s} = -\frac{\alpha k_s (nk)}{k^2 \left((nk)^2 + \varepsilon^2 \right)} \\ \left(n_\nu + i\varepsilon \frac{k_\nu - (nk) n_\nu}{k^2} \right) G_{\nu s} = -\frac{n_s}{k^2} + \frac{\varepsilon^2 + k^2}{\left((nk)^2 + \varepsilon^2 \right)} \cdot \frac{k_s (nk)}{k^4} \end{cases}$$

Having solved this system we obtain the following expression:

$$n_\nu k_s G_{\nu s} = -\frac{(nk)}{(nk)^2 + \varepsilon^2} \left(1 - \frac{(nk)^2}{(nk)^2 + \varepsilon^2} \left(1 + \alpha + \frac{\varepsilon^2}{k^2} \right) \right)$$

$$k_\nu k_s G_{\nu s} = -\frac{(nk)^2}{(nk)^2 + \varepsilon^2} \left(1 - \frac{k^2}{(nk)^2 + \varepsilon^2} \left(1 + \alpha + \frac{\varepsilon^2}{k^2} \right) \right)$$

$$n_\nu n_s G_{\nu s} = -\frac{(nk)^2}{k^2 \left((nk)^2 + \varepsilon^2 \right)} \left(1 - \frac{(nk)^2}{(nk)^2 + \varepsilon^2} \left(1 + \alpha + \frac{\varepsilon^2}{k^2} \right) \right)$$

Multiplying the equation (10) on $\delta_{\mu s}$ we find

$$\delta_{\nu s} G_{\nu s} = -\frac{3}{k^2} + \frac{(nk)^2}{k^2 \left((nk)^2 + \varepsilon^2 \right)} \left(1 - \frac{k^2}{(nk)^2 + \varepsilon^2} \left(1 + \alpha + \frac{\varepsilon^2}{k^2} \right) \right)$$

From the equation(10) it follows that the tensor structure of $G_{\nu s}$ can be submitted as (5). Repeating the operation used above to derive formula (8) we obtain the following expression:

$$\beta_1 = -\frac{1}{k^2}; \qquad \beta_2 = -\frac{(nk)^2}{k^2 \left((nk)^2 + \varepsilon^2 \right)^2} \left(1 + \alpha + \frac{\varepsilon^2}{k^2} \right);$$

$$\beta_3 = 0; \qquad \beta_4 = \frac{1}{k^2} \cdot \frac{(nk) + \frac{1}{2}\frac{\varepsilon^2}{(nk)}}{(nk)^2 + \varepsilon^2};$$

Thus for the gluon Green function we derive the following formula:

$$G_{\nu s} = -\frac{1}{k^2}\left\{\delta_{\nu s} + \frac{k_\nu k_s}{\left((nk)+\varepsilon^2\right)^2}(nk)^2\left(1+\alpha+\frac{\varepsilon^2}{k^2}\right) - \left(k_\nu n_s + k_s n_\nu\right)\frac{(nk)+\frac{\varepsilon^2}{2(nk)}}{\left((nk)^2+\varepsilon^2\right)}\right\}$$

This formula at $\varepsilon \to 0$ coincides with results of the works [3], [4], [8]-[10], [11], [12], [20]. At $\varepsilon = \pm i(nk)$ the last formula (11) have simple dipolar and these poles lie in plane. A rule of detor of poles is usual. From the formula (11) follows that at $\varepsilon \to 0$ and $\alpha = 0$ it cross:

$$n_\mu G_{\mu\nu} = n_\nu G_{\mu\nu} = 0.$$

In finally we note, that the obtained results can be applied for calculation of various quantum-field functions and physical observables in QCD and in any chromodynamics models.

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