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A laser diode with feedback using a fibre delay line as a stable-frequency signal generator and potential fibre sensor

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An optical fibre communication line (OFCL) closed-circuited into a ring network is considered as a controlled automodulated oscillation source. Theoretical and experimental investigations of the amplitude and frequency of automodulation for stationary self-consistent automodulation and external synchronization regimes in such a system are given on the basis of a balance equations analysis. It is shown that this OFCL ring can be used as an optical fibre tester and sensor.

1. Introduction

The development of optical fibre communication lines (OFCL) and their detailed study show that specific modes of operation can be realized in them, allowing the use of certain variants of OFCL in a non-traditional way as controlled self-sustaining oscillation sources and also fibre sensors, which use the change of frequency of those oscillations as an indicator of various ambient influences upon fibres.

The aim of this paper is to analyse some possible regimes in the simplest OFCL, consisting of an optical transmitter, a rather long ($1 \times 10^2 \ldots 5 \times 10^4$ m) multimode or single mode optical fibre and an optical receiver which is closed-circuited into a ring retwork (Fig. 1). When the key in Fig. 1 is on, direct output power self-modulation of the laser diode (LD) of an optical transmitter may occur [1–3]. The modulated light emitted by the LD is detected with the photodetector (PD) of a receiver after propagating for a certain distance through the optical fibre (OF). After being electrically amplified the photodetector signal which is proportional to LD light intensity is applied to the electrical modulator (driver) of the LD. The character of the auto-oscillation in the closed OFCL considered is determined by driver (D) or laser diode (LD) nonlinearity or by that of both of them. As is shown below, under some conditions in the system of Fig. 1 stable automodulation of the LD output light occurs. Its amplitude and frequency depend upon the system parameters.

2. Stationary regime of self-consistent automodulation in the closed-circuited OFCL

The process of stationary intensity automodulation, i.e. self-sustained oscillation intensity of a LD, in the closed-circuited OFCL in Fig. 1 is described by the amplitude and phase balance equations, which can be written as follows:

$$G(\omega, V_{\text{in}})S_{\text{m}}(\omega, I)H(\omega)g(\omega) = 1 \quad (1)$$

$$\varphi(\omega) + \varphi_{\text{m}}(\omega) + [\omega t_0 + \theta(\omega)] + \Psi(\omega) = 2\pi m \quad (m = 1, 2, 3, \ldots) \quad (2)$$

where $G(\omega, V_{\text{in}})$ is the transfer function of the driver (D), depending in common cases upon its input

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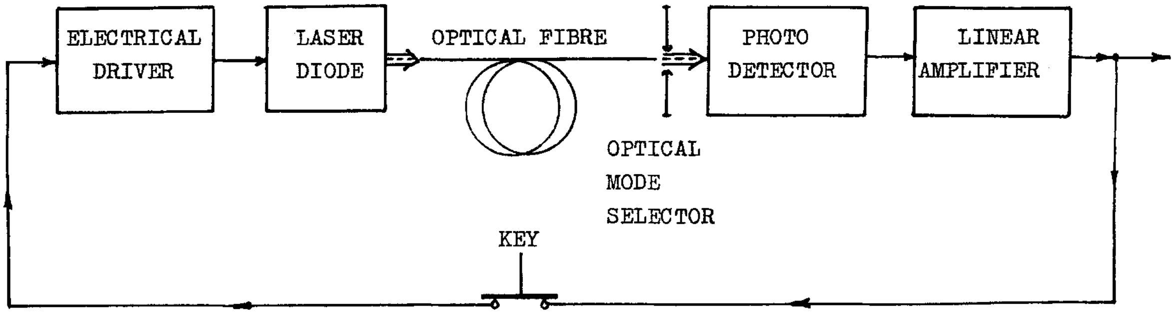

Figure 1 The structural diagram of a closed-circuited optical fibre communication line (OFCL).

amplitude V_{in}; $\varphi(\omega)$ is the phase shift which is determined by driver response time; $S_m(\omega, I)$ is the modulating frequency characteristic of the LD output light, depending on the driver current I injected into LD; $\varphi_m(\omega)$ is the phase shift between the self-sustained intensity oscillation of the LD and the current output of the driver (D) due to the LD response time; $g(\omega)$ and $\Psi(\omega)$ are respectively the transfer function and phase shift of the baseband frequency for the optical receiver; $H(\omega)$ and $\theta(\omega)$ are amplitude and phase frequency responses of the optical fibre, t_0 is the time delay (transit time) of the light propagating along the fibre. In the case of using singlemode optical fibre in OFCL, t_0 is the time defined by Ln/c, where L is the length of the fibre, n is the core refractive index of the fibre and c is the velocity of light in free space.

Values t_0 and $\theta(\omega)$ are determined for the multimode fibres by their mode composition and coupling and input and output launching conditions. Hence it follows that the self-sustained oscillation frequency ω can be adjusted by changing LD launching conditions and selecting mode groups of the light coming out of the fibre and feeding into the optical detector. It can be done, for example, by inserting an optical mode selector (a lens-pinhole spatial filter in Fig. 1) between the output end face of the fibre and detector. As some external factors such as changes in pressure, vibration, temperature, etc., can influence the mode composition and other properties of light passing through the optical fibre, the value $\omega t_0 + \theta(\omega)$ changes. According to Equation 2 that leads to changes in the automodulation frequency and makes it possible to use the system shown in Fig. 1 as a fibre sensor. An important feature of sensors of this type is that the frequency ω can be measured with high precision if it is sufficiently stable. Fortunately, one of the properties of the system in Fig. 1 is high automodulation frequency stability, when the optical fibre length in this system is sufficiently long. Indeed, considering our system as some specific oscillator with an optical fibre delay line and assuming that a resonance element of this system is for example the driver (D), we can write the transfer function of this element as

$$G(i\omega) = G(\omega_r, V_{in})/[1 + i(\omega - \omega_r)T_r] \tag{3}$$

where ω_r is the resonance angular frequency of the filtering link, T_r is the resonance element time constant. It is easy to obtain from Equation 2 the formula characterizing a stabilizing effect of a fibre delay line on a self-sustained oscillation frequency ω_{osc} in the stationary regime:

$$(\omega_{osc} - \omega_m)/\omega_m \simeq (T_r/t_0)[(\omega_r - \omega_m)/\omega_m] \tag{4}$$

where ω_m is one of the frequencies, which are determined by the natural number $m = 1, 2, 3, \ldots$ of wavelengths that can be spaced along the fibre. Thus the oscillation frequency ω_{osc} is first of all determined by the frequency ω_m which is close to the linear amplifier centre frequency ω_r (or the resonance frequency ω_r of the bandpass filter). Assuming that in Equation 4, $T_r/t_0 = 1 \times 10^{-3}$ and the initial relative frequency instability $(\omega_r - \omega_m)/\omega_m = 1 \times 10^{-6}$, we obtain the instability of the automodulation frequency of our system $(\omega_{osc} - \omega_m)/\omega_m = 1 \times 10^{-9}$ or 10^3 times better. At high frequencies (about 0.5 GHz and higher), the role of a resonant bandpass filter in the system in Fig. 1 can be played by the LD itself, since its frequency characteristic $S_m(\omega, I)$ given by small signal analysis

[3] has a form similar to Equation 3

$$S_m(\omega, I) = S_m(\omega_0, I)/[1 + i(\omega - \omega_0)\tau_{LD}] \qquad I \to 0 \tag{5}$$

where

$$\omega_0 \simeq [(I_0/I_{th} - 1)/(\tau_s \tau_{LD})]^{1/2} \tag{6}$$

is the frequency of relaxation self-oscillation of the LD light output, I_{th} is the threshold current of the LD, I_0 is the bias current of the LD, τ_s is the spontaneous carrier lifetime of LD, $\tau_{LD} = 2(I_{th}/I_0)\tau_s$ is the duration of the LD damping relaxation oscillations.

Taking into account Equations 5 and 6 and the inequality $\tau_{LD}/t_0 \ll 1$ when the approximation $\omega_{osc} \simeq \omega_m \simeq \omega_0$ takes place, it follows from Equation 4 that in closed-circuited OFCL the automodulation frequency ω_{osc} can be electrically controlled by a change of the bias current I_0 or the threshold current I_{th} of the LD. In practice the frequency range of this control is determined by the frequency band where the threshold conditions for onset of the autopulsation in our system (Fig. 1) take place. The experimentally measured frequency $\omega_0/2\pi$ for the conventional AlGaAs–DH stripe laser diodes as a function of $[I_0/(I_{th} - 1)]^{1/2}$ can be changed changed from 0.5 GHz to 2–3 GHz [4].

3. External synchronization in closed-circuited OFCL

Let us note the general features of the self-modulation oscillations (autopulsation) frequency synchronization in the closed-circuited OFCL on its fundamental harmonic. As in the paper by Dvornikov *et al.* [5] for the system shown in Fig. 1 we can write down that a locking bandwidth B is approximately:

$$B \simeq (k_s/V_0)(1 + A^2)^{1/2} \tag{7}$$

where k_s is some coefficient that is proportional to the synchrosignal amplitude, V_0 is the free-running autopulsation amplitude and A is the non-isochronicity coefficient of the system.

The value of A for the free-running self-sustained oscillator operating on such frequencies when we can neglect the dispersion properties of the fibre is:

$$A = k(\omega)\xi(1 + \xi^2)^{1/2}/(1 + a + a\xi^2) \tag{8}$$

where $k(\omega)$ is the coefficient which is proportional to the signal gain in the open-circuited OFCL (Fig. 1), $\xi = T_r(\omega_k - \omega_r)$, $a = t_0/T_r$ and ω_k is one of the resonance frequencies of the linear part of the system in Fig. 1. The values of ω_k are determined as in the work of Dvornikov *et al.* [5]. Within the locking bandwidth B the autopulsation amplitude V_s depends upon the phase difference Δ_s between a sine-wave autopulsation and a synchrosignal as:

$$V_s = V_0 + k_s \cos(\varphi_s + \Delta_s) \tag{9}$$

where $\varphi_s = -\arctan A$.

It follows from Equations 7–9 that in the general case the dependence of the amplitude V_s upon the angular frequency difference $(\omega_s - \omega_k)$ is asymmetrical and only when $\omega_r = \omega_k$ does it become symmetrical. Besides, it is evident that the locking bandwidth B and amplitude V_s decrease with an increase in $(\omega_s - \omega_k)$.

4. Experimental details

In the experimental system in Fig. 1 we used a conventional commercial AlGaAs–DH LD as a light source. Two multimode graded-index optical fibres 130 m and 400 m long, NA – 0.4, and losses about 7 dB km^{-1} were used as a delay line. The linear amplifier of the optical receiver and the electrical driver (D) of the optical transmitter were made as a multicascade scheme containing a resonant signal-circuit received set frequency-selective cascade with resonance frequency near to 30 MHz. The net gain of cascade-connected LA and D was 60 dB.

Fig. 2 shows the observed adjustment curves of the fibre delay line controlled self-sustained oscillation (autopulsation) frequency $\nu_{osc} = \omega_{osc}/2\pi$. One can see that a degree of the frequency stabilization increases according to Equation 4, when the fibre delay line becomes longer. In

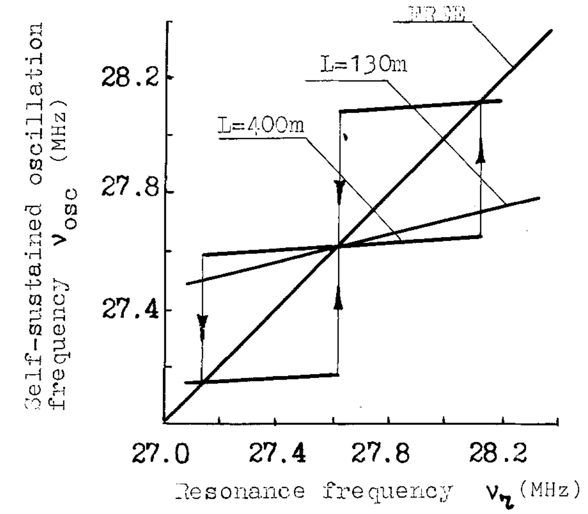

Figure 2 Relations between the sine-wave automodulation frequency $\nu_{osc} = \omega_{osc}/2\pi$ and the linear amplifier (LA) centre frequency ν_r measured for three fibre lengths $L = 0$, 130 and 400 m.

particular, for the fibre length $L = 400$ m, when the time constant T_r of the resonant frequency-selective circuit was sufficiently less than the transit time $t_0 \simeq Ln/c$ ($T_r/t_0 = 0.1$), these measurements gave $\Delta\omega_{osc}/\omega_{osc} = 1 \times 10^{-7}$. The behaviour of the automodulating frequency transitional process after onset of the OFCL supply voltage V_g is shown by the broken lines in Fig. 3. The corresponding absolute frequency change $\Delta\nu = \nu_{osc} - \nu_m$ is shown in this figure by solid lines.

The frequency synchronization of the self-sustained oscillations in the system in Fig. 1 was realised in two ways; directly by an electrical synchrosignal output from a standard r.f. generator and then by an optical synchrosignal light output of the sine-wave intensity modulated LD. In the first case the synchrosignal was injected into the electrical driver (D) input and in the second case it was fed into the Si-APD detector. It was found that the frequency ν_{osc} of the self-oscillating closed-circuited OFCL in Fig. 1 was locked to the incident synchrosignal frequency ν_s when the frequency difference $\nu_s - \nu_{osc}$ was smaller than a certain locking bandwidth B. The measurements of this locking bandwidth B and another parameter such as an amplitude of synchronized oscillation, etc. conducted with the help of these two synchronization techniques showed similar results. In Fig. 4, as an example, the normalized automodulated oscillation amplitude $V_s/V_{s\,max}$ as a function of the synchrosignal frequency ν_s for

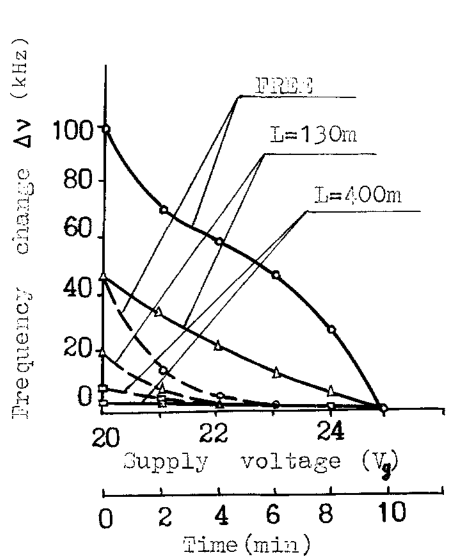

Figure 3 The observed frequency change $\Delta\nu = \nu_{osc} - \nu_m$ as a function of the supply voltage V_g of the optical receiver linear amplifier (solid line) and time t for the transitional process in the system in Fig. 1 (broken line) for three fibre lengths $L = 0$, 130 and 400 m.

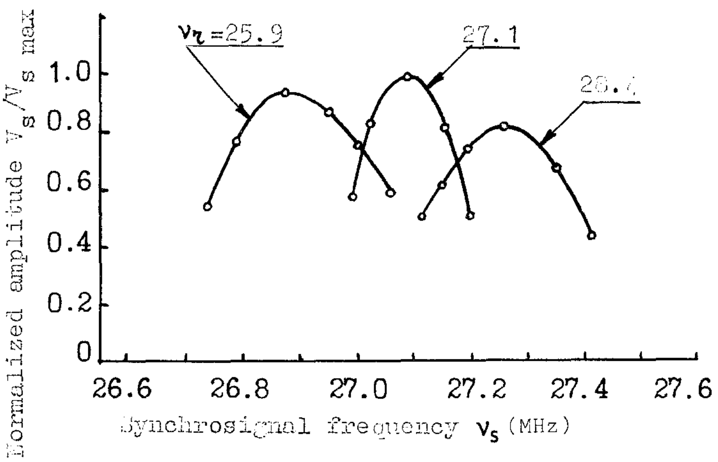

Figure 4 Normalized automodulated oscillation amplitude $V_s/V_{s\ max}$ versus the synchrosignal frequency ν_s for the different values of the resonant frequency ν_r of the LA (passband filter).

certain capacitance tunings of self-resonant frequency ν_r of the passband filter for injection locking by electrical synchrosignal frequency.

Experiments were carried out to estimate the influence of fibre geometrical length and temperature upon automodulation frequency. The fibre length was changed by breaking its output end. The sensitivity of the device described to the fibre length variation was about 65 Hz mm^{-1} for an automodulation frequency of ~30 MHz with its stability of ~ 1×10^{-7} during a period of 10 min and a fibre length equal to 400 m. That means that absolute sensitivity is about 5×10^{-2} mm. To obtain such highly precise measurements of fibre length changes with the help of the traditional time- or frequency-domain methods is rather difficult.

The influence of the fibre temperature variations on the automodulation frequency was also studied for the automodulation frequency of ~30 MHz. It was found that for a quasistatic temperature change (from 288 to 328 K) of the fibre plunged into the water bath the dependence of the automodulation frequency on the fibre temperature was almost linear with the steepness of about 400 Hz K^{-1}. These data allow us to measure slow temperature variations of about $\geqslant 1 \times 10^{-2}$ K, if the automodulation frequency stability in the device described is equal to ~ 1×10^{-7}. Automodulation frequency tuning was also studied with the help of selecting fibre modes received by the photodetector through increasing the distance between the photodetector and the fibre output end up to 15 cm. That results in a relative automodulation frequency of over 0.2%.

5. Conclusions

It is established that for some conditions in closed-circuited OFCL single-frequency automodulation oscillations appear, whose frequency may be tuned over a wide range at the cost of laser diode current changes and mode selections. Automodulation frequency stability increases greatly with an increase of fibre length up to several hundred metres.

The device described can be used for measuring differential fibre mode delay, small fibre length variations and as a fibre sensor of temperature, pressure, and so on.

The main advantage of fibre sensors of this type is in registering ambient effects on fibres by means of automodulation frequency, a physical quantity which can be measured at present with very high precision.

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